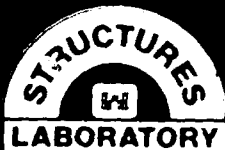




US Army Corps
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EXPLOSIVE TESTS ON REINFORCED CONCRETE WALLS AT CAMP SHELBY, MISSISSIPPI

by

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Structures Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631



July 1986
Final Report

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US Army Corps of Engineers
Washington, DC 20314-1000
Under Project No. 4A762719AT40
Task Area A0, Work Unit 023

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<p>> An existing 18-in.-thick reinforced concrete wall was tested using close-in detonations of cased and bare explosive charges. The objectives of the tests were to gather data on the loading of the wall and to determine the difference in wall response between cased and bare charges. Both composition C-4 and TNT explosives were used in the tests. As expected, the results showed the C-4 to be more energetic than the TNT and the cased charges to be more damaging than the bare ones. The failure mode for this particular wall was one of interior spalling followed by direct shear near the supports.</p>		

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Director of WES was COL Allen F. Grum, USA. Technical Director was Dr. Robert W. Whalin.

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CONTENTS

	<u>Page</u>
PREFACE.....	1
CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT.....	3
PART I: INTRODUCTION.....	4
Background.....	4
Objectives.....	4
PART II: TEST PROCEDURES.....	5
Approach.....	5
Test Structure.....	5
Test Setup.....	6
Explosive Charges.....	6
Instrumentation and Photography.....	7
PART III: TEST RESULTS.....	8
Airblast.....	8
Fragment Velocity.....	8
Structural Response.....	8
PART IV: ANALYSIS OF RESULTS.....	10
Blast Loading.....	10
Structural Response.....	10
PART V: CONCLUSIONS.....	12
TABLES 1-4	
FIGURES 1-29	
APPENDIX A: BLAST PRESSURE DATA.....	A1
APPENDIX B: COMPARISON OF TIME-OF-ARRIVAL DATA.....	B1

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
inches	2.54	centimetres
kip (force) per square inch	6.894757	megapascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic inch	27.6799	grams per cubic centimetre

EXPLOSIVE TESTS ON REINFORCED CONCRETE WALLS
AT CAMP SHELBY, MISSISSIPPI

PART I: INTRODUCTION

Background

1. Because of a lack of data, design procedures for aboveground reinforced concrete facilities to resist the effects of near-miss detonations of conventional bombs rely on several conservative assumptions. As a result, these semihardened facilities are designed with overly conservative and expensive steel reinforcement.

2. The US Army Engineer Waterways Experiment Station (WES) is conducting a long-term research program on deliberate hardened facilities to evaluate several aspects of the response of both aboveground and buried structures to near-miss explosions. In support of this program, a series of five tests was conducted in March and April of 1982 at Camp Shelby, Mississippi. An existing structure, which was built and previously tested in conjunction with another WES program, was used for the tests. Although there was existing damage to the structure from the previous test, it was slight and was judged insignificant in affecting the results of the planned tests.

Objectives

3. The objectives of the tests were twofold: (a) to gather data on the loading of the structure wall from nearby surface detonations of bare and cased TNT and bare C-4 charges, and (b) to determine the difference in wall response from cased and uncased charges.

PART II: TEST PROCEDURES

Approach

4. An existing, slightly damaged, reinforced concrete structure, consisting of a front test wall, side support walls, a floor slab, and a roof slab was used for the test. Three tests were conducted against the front wall using bare and cased TNT and bare C-4 charges. The wall was instrumented to gather interface airblast loading data. In the last two tests, bare and cased TNT charges were tested against the side support walls. No instrumentation was used in these tests. High-speed cameras were used in all tests to observe wall response and to record fragment velocities. Pre-test and posttest still photographs were taken of the test setup, and wall damage and posttest measurements were made of the extent of wall damage and the deflection of the wall.

Test Structure

5. Sketches of structural details are given in Figure 1. The vertical steel reinforcement in the front wall consisted of No. 8 bars on 6-in.* centers for the interior face and No. 4 bars on 12-in. centers for the outside face. Therefore, the reinforcement ratio was 0.9 percent in the interior face and 0.11 percent in the exterior face. Horizontal reinforcement consisted of No. 4 bars on 9-in. centers in each face for a 0.17-percent ratio in each face. For the side wall, vertical reinforcement consisted of No. 8 bars on 8-in. centers for the exterior face (for a ratio of 0.67 percent) and No. 9 bars on 7-in. centers for the interior face (for a ratio of 0.98 percent). Horizontal reinforcement consisted of No. 5 bars on 11-in. centers (0.2 percent) in each face. There was a cold joint at the junction of the floor and walls, and dowels extended across this joint to tie the two members together structurally. The dowels consisted of No. 8 bars on 8-in. centers in the exterior face (0.67 percent) and No. 8 bars on 11-in. centers in the interior face (0.76 percent).

* A table of factors for converting non-SI to SI (metric) units of measurement is presented on page 3.

6. During construction, four steel reinforcement bar samples were taken for each size bar and tested for yield and ultimate strength. The results are given in Table 1. The steel was specified as American Society for Testing and Materials (ASTM) A 615-68, Grade 60. Concrete samples were also taken during construction of the walls. The average 28-day compressive strength of six test cylinders was 4,321 psi. The walls were cast on 28 October 1982. After completion of the structure, an impact test was conducted to determine the natural frequency and mode shapes of the wall. The fundamental frequency was determined to be 48.6 Hz. As mentioned, the structure was constructed for another test program and was tested initially on 18 December 1981. This test left the front wall structurally sound with a maximum permanent deflection of only 0.05 in. and with numerous hairline cracks, as shown in Figure 2 (after highlighting with a black felt-tipped marker). The lines shown painted on the wall are 2-ft squares. No damage resulted to the side walls.

Test Setup

7. The tests were conducted from 31 March through 2 April 1982. The setup for the tests is shown in Figure 3, and the test parameters are listed in Table 2.

Explosive Charges

8. Five charges were fabricated; four were made using cast TNT (density of approximately 0.057 lb/in.³) and one was made with hand-packed composition C-4 (density 0.057 lb/in.³). All charges were cylindrical with a length of 30 in. and a diameter of 12.75 in. for a charge weight of approximately 218.5 lb. The C-4 charge and two of the TNT charges were bare. The other two TNT charges were cast in a steel tube with an inside diameter of 12.75 in. and a wall thickness of 0.25 in. The tubes were fabricated from a structural steel plate by cold rolling to the proper dimensions and welding a seam along the length. A circular plate was then welded to the bottom, and lifting lugs were placed on each side near the top. The charges had booster wells cast or formed into the center of the top end. A small amount of C-4 was placed in the well and mounded to form a place for insertion of the blasting cap. All charges were detonated at the center top using a Reynold's Industries RP83 detonator.

Instrumentation and Photography

9. Instrumentation for the first three tests consisted of airblast gages placed in the front wall of the structure and an airblast gage placed flush with the ground surface. The gage layout is shown in Figure 4. All gages were Kulite Corporation Model No. HKS-375. Table 3 gives the pertinent data concerning the gages used in the test. All gages were mounted so that the gage face was flush with the exterior face of the wall or with the ground surface.

10. On Tests 1, 2, 4, and 5 a single high-speed camera with a frame rate of 4,000 frames/sec was used to view the rear of the test wall. For Test 3, an additional camera with a frame rate of 8,000 frames/sec was used to view a fragment witness panel. Still photographs were used to document pretest and posttest conditions.

PART III: TEST RESULTS

Airblast

11. Appendix A gives the pressure-time histories as digitized and plotted from the analog data for each of the pressure gages in the first three tests. Pertinent information taken from these records is given in Table 4. Figures 5 through 7 are comparative plots of the peak pressure, impulse, and time of arrival for each test. Data from several gages are missing due to gage malfunction or erroneous readings. As can be seen from the results, peak pressures occurred near the bottom of the wall and were on the order of 4,300 psi.

Fragment Velocity

12. High-speed cameras were used to view a fragment witness panel in Test 3 in an attempt to obtain data on the velocities of case fragments. However, due to unforeseen technical problems, the camera did not begin filming until after the detonation, and no data were obtained.

Structural Response

13. Figures 8 through 29 show the pretest and posttest conditions of the walls. After each of the tests, the maximum permanent deflection of the walls and the extent of major spalling or breaching were measured. The results were:

- a. Test 1. The test resulted in no measurable permanent deflection. Some of the existing hairline cracks were widened and a few new cracks formed on the rear of the wall (Figure 11). The front of the wall saw no damage other than some of the existing 4 in. of Styrofoam insulation being blown off, and blackening of the wall surface (Figure 10). There was a noticeable crack formed in both of the side walls (Figure 12a and b).
- b. Test 2. Spalling occurred on both the front and back of the wall. The spall on the front wall was approximately 10 ft wide and 3 ft high at the highest point (Figures 14 and 15); on the rear, it was approximately 6 ft wide and 2 to 3 ft high (Figures 16 and 17). The spall penetrated no deeper than the depth of the inside of the rebars (approximately 4 in.) on both the front and back. There was a 4- to 5-ft-high large crack at the

bottom of the wall near both side walls (Figure 18). There was a 2-in. permanent deflection on the No. 8 dowels on the rear face near the bottom of the wall.

- c. Test 3. This test resulted in a breach of the wall (Figure 21). Dimensions of the breach on the front of the wall were approximately 13 by 4 ft. Numerous fragment impacts were noted along the bottom of the wall in and near the breached area. The limit of spalling and breaching on the rear of the wall extended 16 ft across the bottom and approximately 6 ft up the wall (Figure 22). The No. 8 dowels and vertical rebars were bent outward. The ends of the dowels had a permanent deflection of 24 in.
- d. Test 4. There was no spalling on either side of the wall except near the free edge due to edge effect. There was major cracking of the outside of the wall (Figure 24) with a permanent deflection of the wall surface of approximately 0.5 in. inward. The inside of the wall was cracked (Figure 25) and the bottom of the wall (at the cold joint) was deflected 4.5 in. (Figure 26).
- e. Test 5. The outside of the wall was spalled and cratered by the blast and fragment impact to a depth of approximately 5 in. (Figure 28). The width and height of the area of exposed rebar was 6 by 2.5 ft. Numerous fragment impacts were noted along the bottom of the wall. On the inside of the wall, spalling had exposed the rebar for the entire 9-ft width of the wall and for a height of approximately 3 ft (Figure 29). The ends of the dowels were exposed and bent outward approximately 12 in. from the wall. Near the bottom of the wall the dowels appeared to have a permanent deflection of around 4 in. The concrete was spalled to a depth of approximately 9 in. and the remaining 4 in. of concrete was crushed to the extent that a hole could easily be opened through the wall using a metal rod.

PART IV: ANALYSIS OF RESULTS

Blast Loading

14. Analysis of the test results indicated the following points with respect to blast loading:

- a. Comparison of the peak pressures shows that, as expected, the greatest pressures existed near the bottom of the wall. Comparison of the peak pressures at gage PQ1 shows extraordinary differences between the C-4, TNT, and cased TNT charges. However, these differences are plausible since the gage was located near the angle of incidence where reflection factors changed drastically. In general, no conclusions could be drawn as to the relative effectiveness of the different charges by examination of the peak pressure data alone.
- b. Comparison of impulse data is also nonconclusive, with the greatest differences being in gage location PQ1.
- c. The time of arrival data were the most consistent, particularly when comparing the bare TNT to the bare C-4. The Air Force Weapons Laboratory analyzed the data using the SEDOV similarity solution and concluded that the C-4 was 34 to 38 percent more energetic than the TNT, and that the airblast from the bare TNT was somewhat greater than that of the cased TNT (Appendix B).

Structural Response

15. Analysis of test results indicates the following points with respect to structural response:

- a. No comparisons can be made between Tests 2 and 3 or 1 and 3, since the damage was cumulative. Although no damage was evident from the first test, calculations indicate that spall cracks could have occurred inside the wall. Thus, comparisons of Tests 1 and 2 may be in error. However, the greater damage seen in Test 2 is in agreement with the blast data, which indicate that C-4 is more energetic than TNT.
- b. Comparisons between Tests 4 and 5 are the most accurate. It is obvious that the casing has a significant effect on the level of damage. The first three tests indicate that the blast effects are close to the same (bare TNT being somewhat greater). Thus the increase in damage is probably due to the concentration of energy from the impact of the case fragments in a narrow band near the bottom of the wall. It should be noted that although the damage to the walls was significantly different, structurally the walls were probably similar with neither being capable of carrying much load. (In fact, after the last test, a bulldozer was able to tip the total structure, making it so unstable that it fell down.) The damage from

Test 4 indicates that just a slight increase in the loading (such as from the impact of the case fragments) could probably create the damage seen in Test 5.

- c. In all tests except Test 1, the major damage was confined to the region near the bottom center of the wall. It was also here that the largest deflections occurred. As with previous tests of this type, the failure mechanism seems to be one of direct shear at the support or in some cases the cold joint. Test 4 shows the direct shear type of failure most dramatically, and also indicates that part of the wall may actually suffer spall cracks inside the wall and then be failing in direct shear.

PART V: CONCLUSIONS

16. Based on the results obtained in this series of tests, the following conclusions may be drawn:

- a. C-4 is more energetic than TNT. Analysis of test results indicates a factor of 1.34 to 1.38.
- b. There is an increase in loading of the wall due to case fragment impact. For Tests 4 and 5, this produced a dramatic difference in the damage.
- c. The failure mode for this particular type of reinforced wall appears to be one of interior spalling followed by direct shear near the supports.

Table 1
Results of Strength Tests of Reinforcement Bars

<u>Bar Size</u>	<u>Yield Strength ksi</u>	<u>Ultimate Strength ksi</u>
No. 4	67.7	106.0
No. 5	66.2	101.4
No. 6	62.6	105.0
No. 8	63.9	105.1

Table 2
Test Parameters

<u>Test No.</u>	<u>Charge</u>	<u>Distance from Wall</u>
1	Bare TNT	7 ft 4-1/2 in.
2	Bare C-4	7 ft 4-1/2 in.
3	Cased TNT	7 ft 4-1/2 in.
4	Bare TNT	5 ft 6 in.
5	Cased TNT	5 ft 6 in.

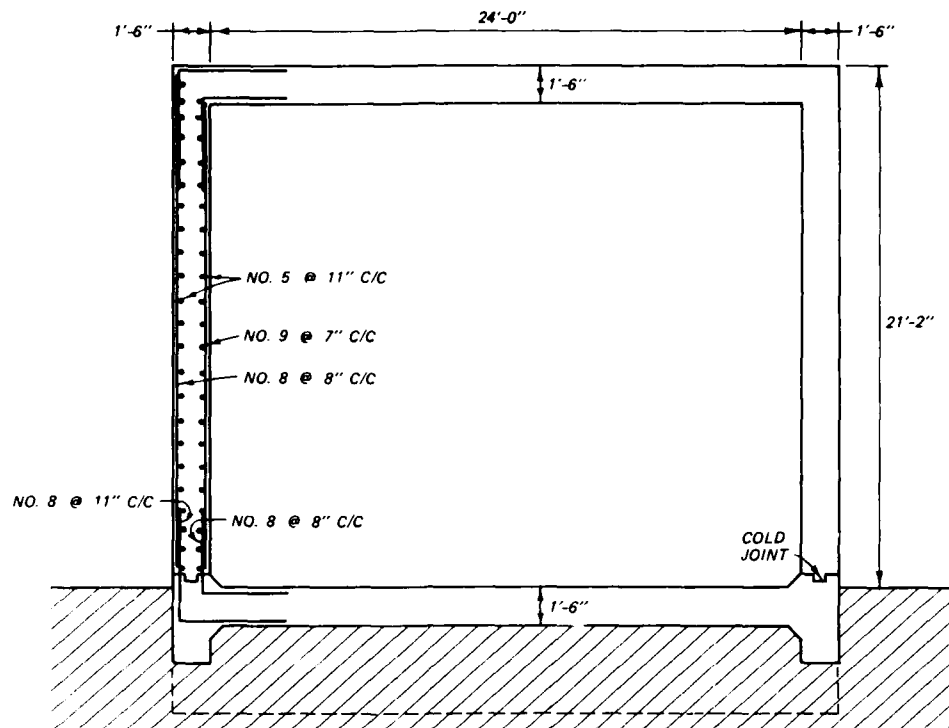
Table 3
Gage Information

<u>Gage No.</u>	<u>Rate Pressure, psi</u>	<u>Natural Frequency, kHz</u>
IOP	5,000	675
PM1	20,000	725
PM2	5,000	675
PM3	1,000	500
PQ1	5,000	675
PQ2	5,000	675
PQ3	1,000	500
PS1	5,000	675
PS2	1,000	500
PS3	1,000	500

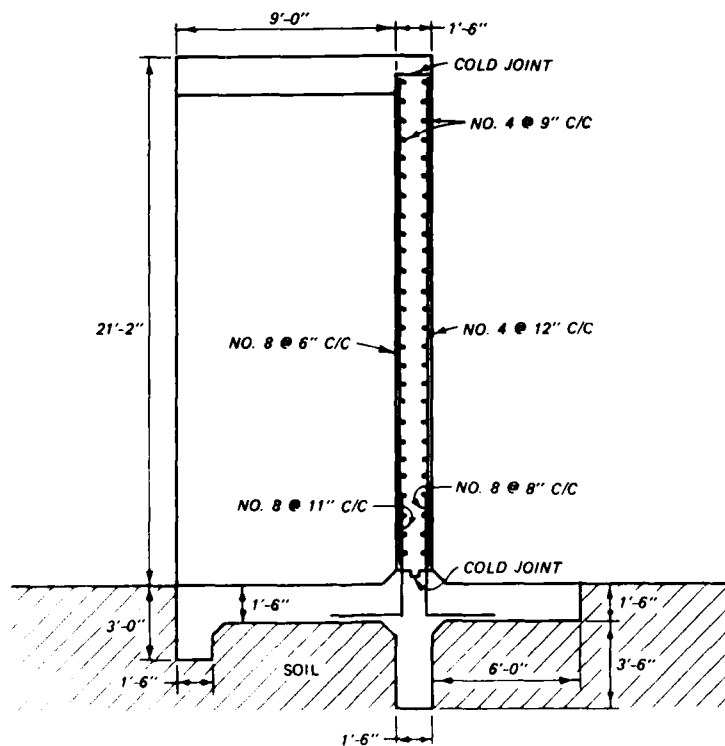
Table 4
Blast Data

Gage No.	Peak Pressure, psi			Impulse, psi-msec			Arrival Time, msec		
	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
	Bare TNT	Bare C-4	Cased TNT	Bare TNT	Bare C-4	Cased TNT	Bare TNT	Bare C-4	Cased TNT
IOP	1,596	1,606	770	170	165	135	0.67	0.69	0.98
PM1	4,318	No data	No data	1,000	No data	No data	0.81	No data	No data
PM2	950	550*	1,095	450	No data	450	1.60	1.40	1.60
PM3	393	651	503	250	330	250	2.64	2.50	2.50
PQ1	1,043	3,523	2,633	520	760	780	1.02	0.85	1.25
PQ2	747	603	831	360	280	370	1.88	1.50	1.44
PQ3	279	207	188	115	140	130	3.17	2.82	3.05
PS1	824	903	956	330	330	No data	1.66	1.33	1.84
PS2	413	524	317	220	220	220	2.31	1.90	2.51
PS3	278	354	234	170	190	165	3.71	3.20	3.81

* Questionable data.



a. Rear view of cross section showing rebar in one of the side walls



b. Side view of cross section showing rebar for front wall

Figure 1. Structural details

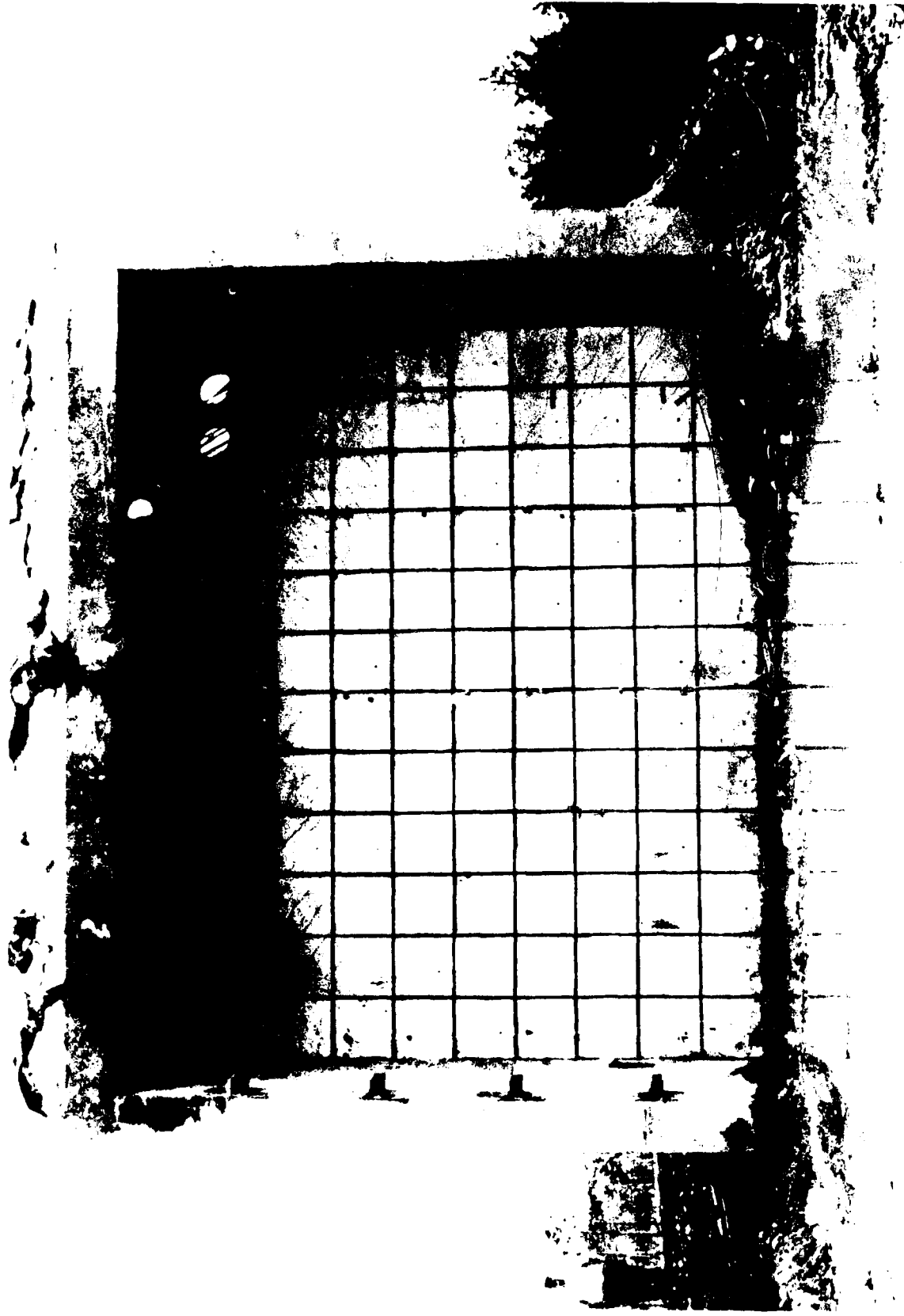


Figure 2. Existing damage to test structure as viewed from rear

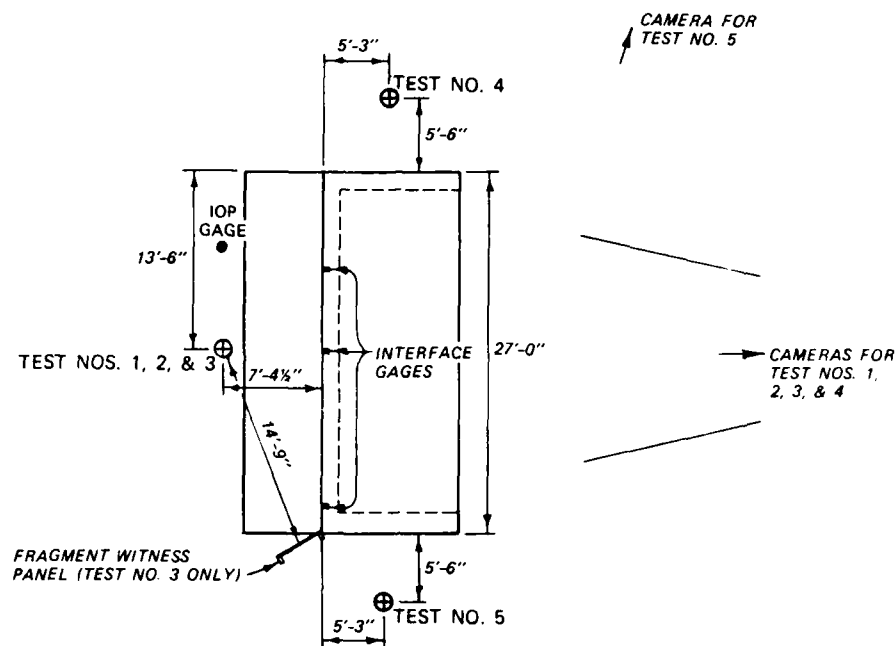


Figure 3. Test setup

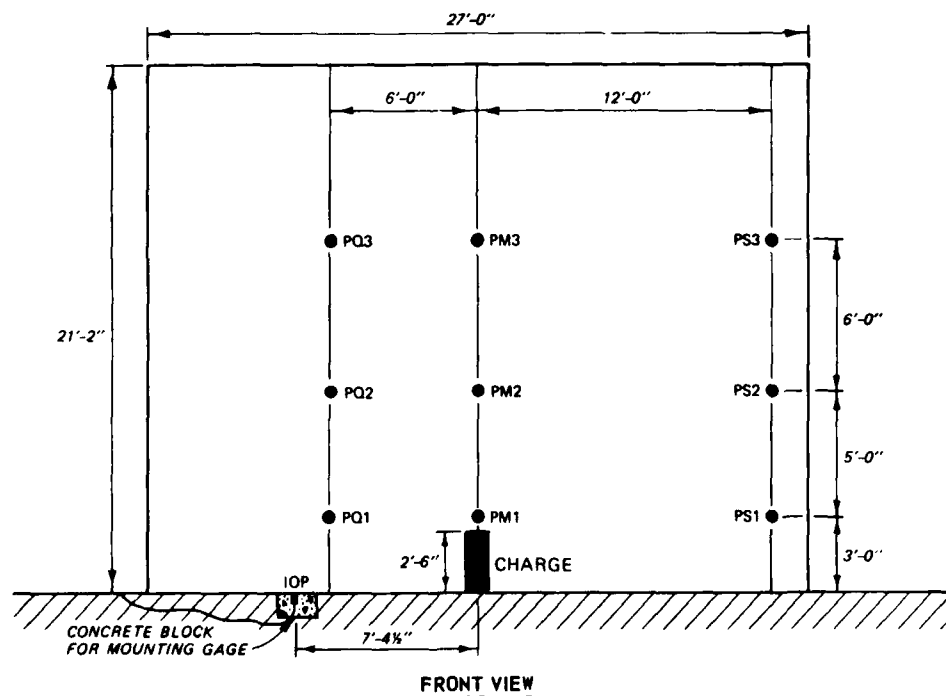


Figure 4. Gage layout for Tests 1-3

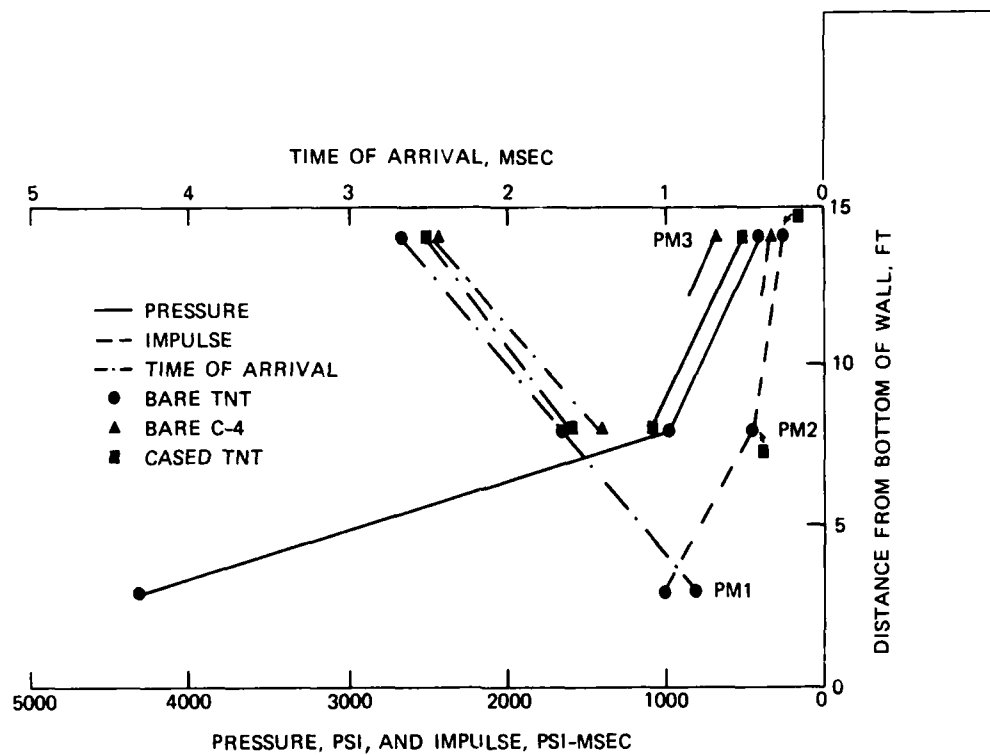


Figure 5. Comparison of blast pressure data for gages PM1, PM2, and PM3

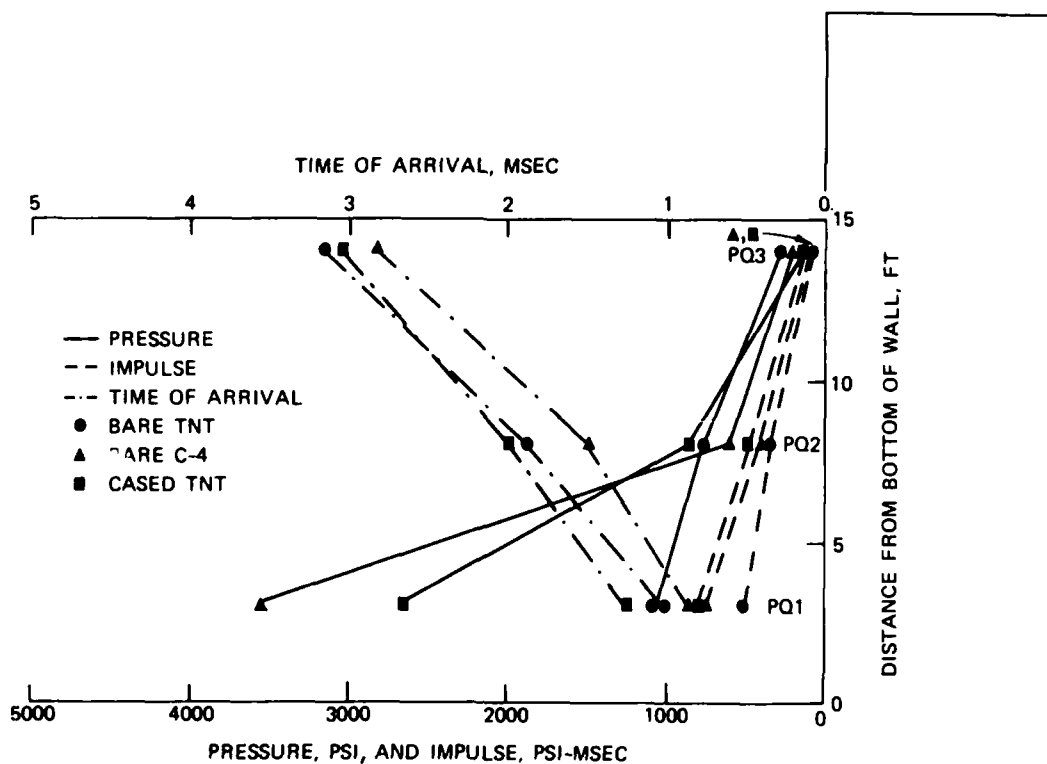


Figure 6. Comparison of blast pressure data for gages PQ1, PQ2, and PQ3

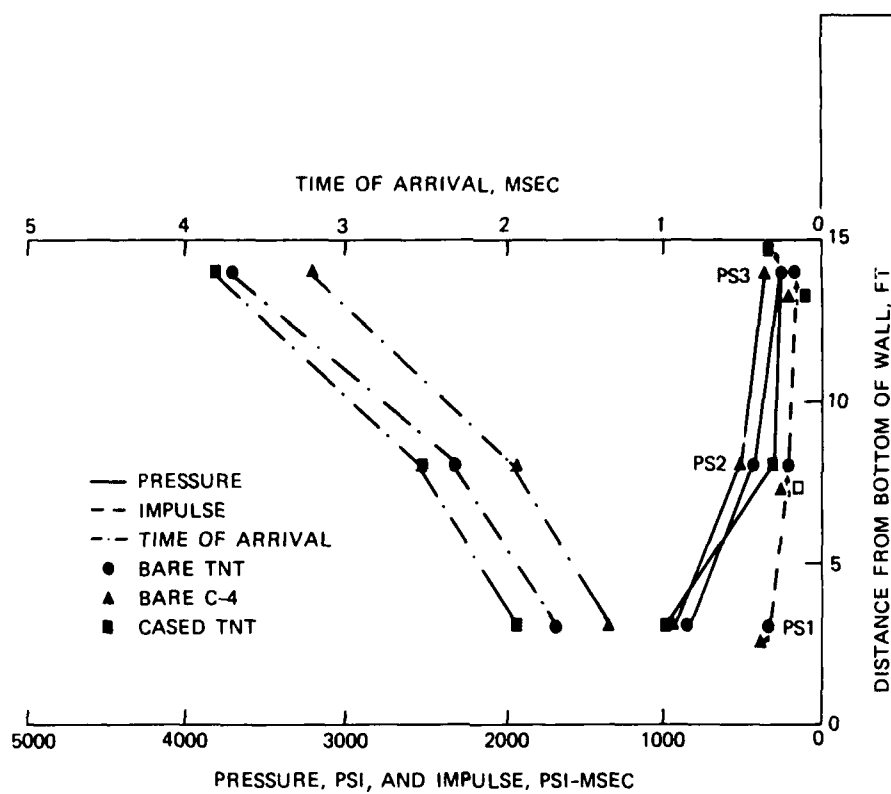


Figure 7. Comparison of blast pressure data for gages PS1, PS2, and PS3

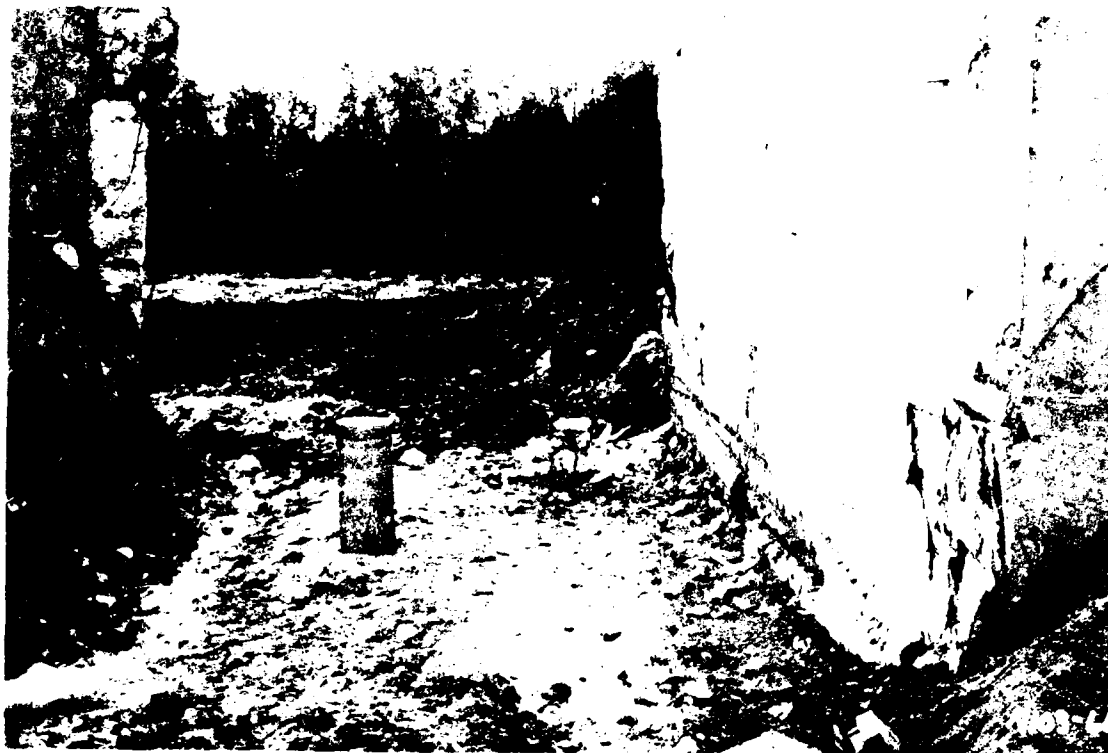


Figure 8. Bare TNT charge in position for Test 1

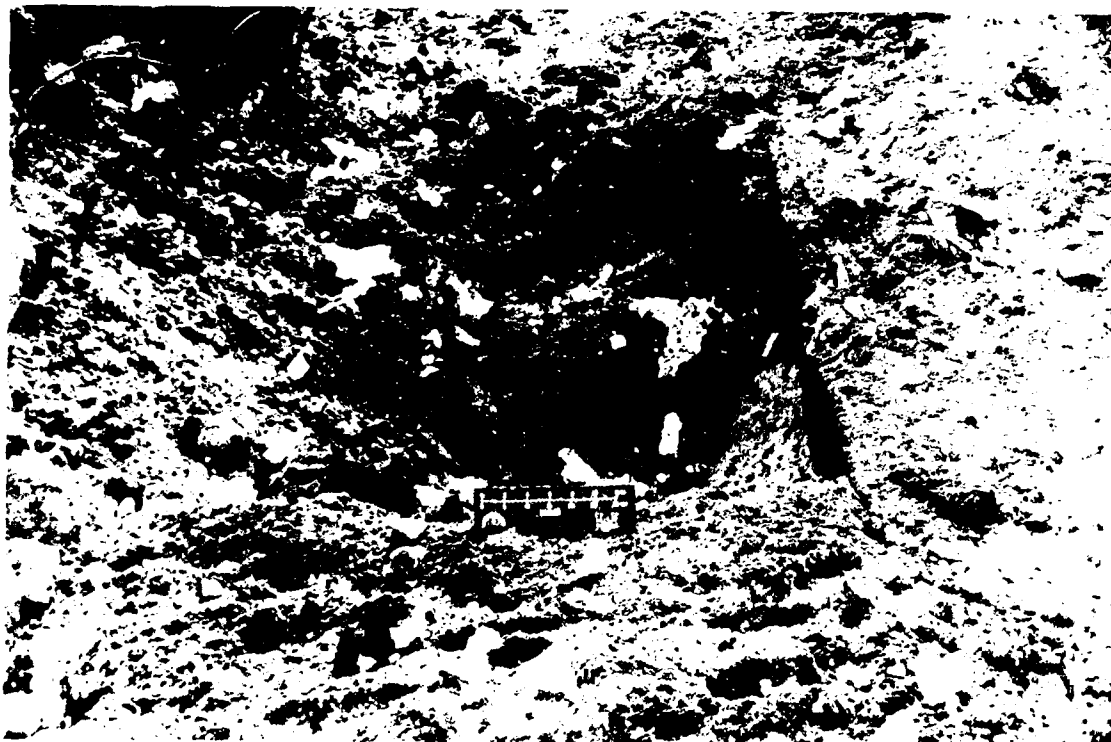


Figure 9. Crater formed from detonation of bare TNT charge



Figure 10. Blackening of wall from bare TNT explosion

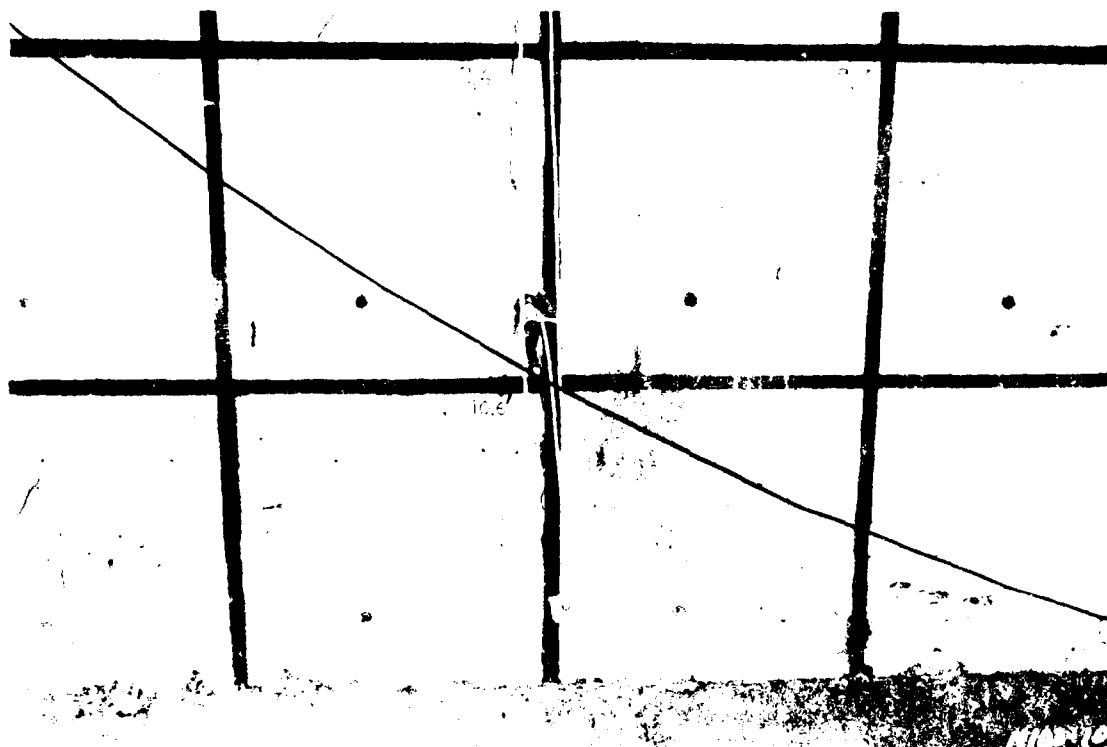
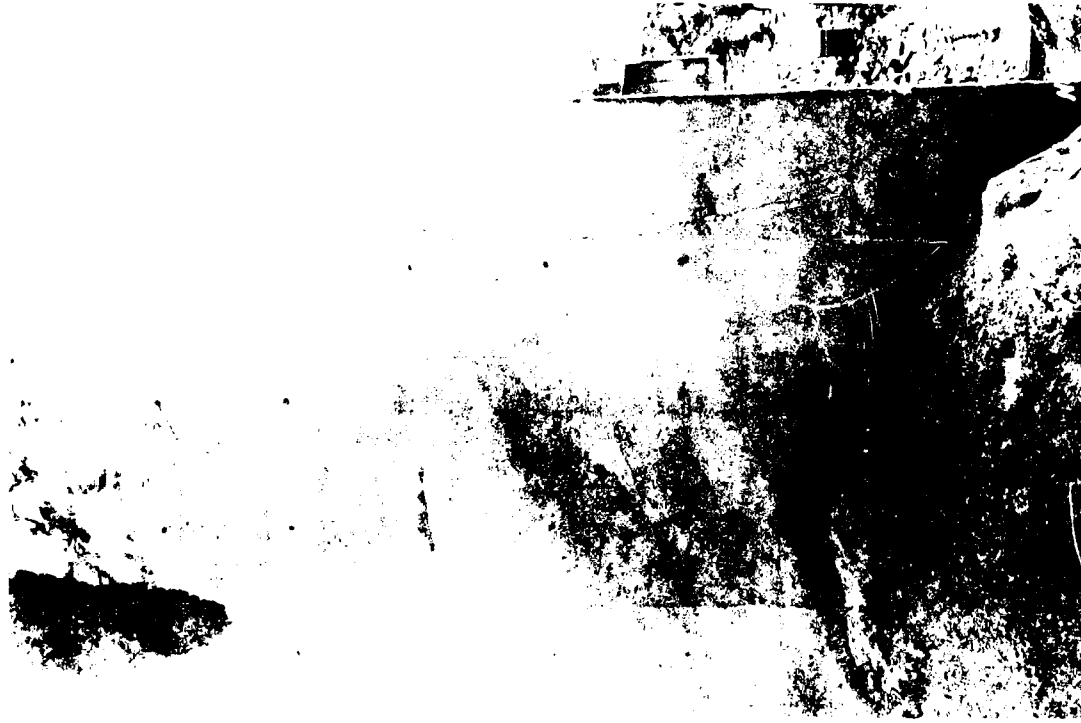
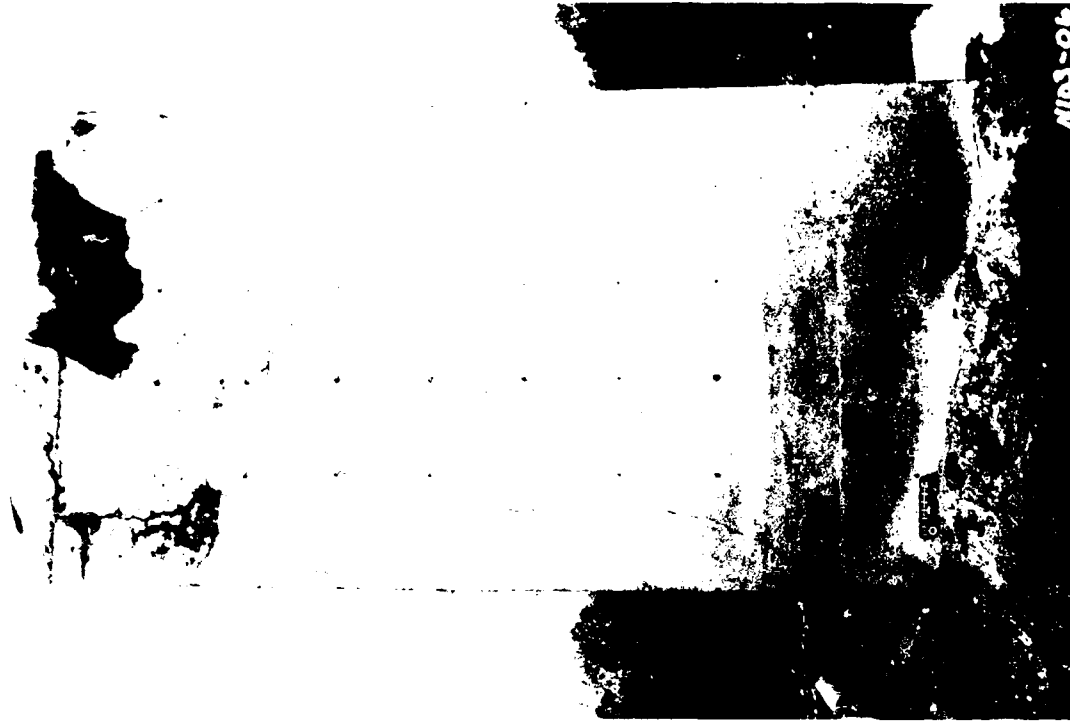


Figure 11. Crack pattern near bottom center rear of wall resulting from Test 1



a. Close-up view



b. Overall view

Figure 12. Cracking of side walls from Test 1

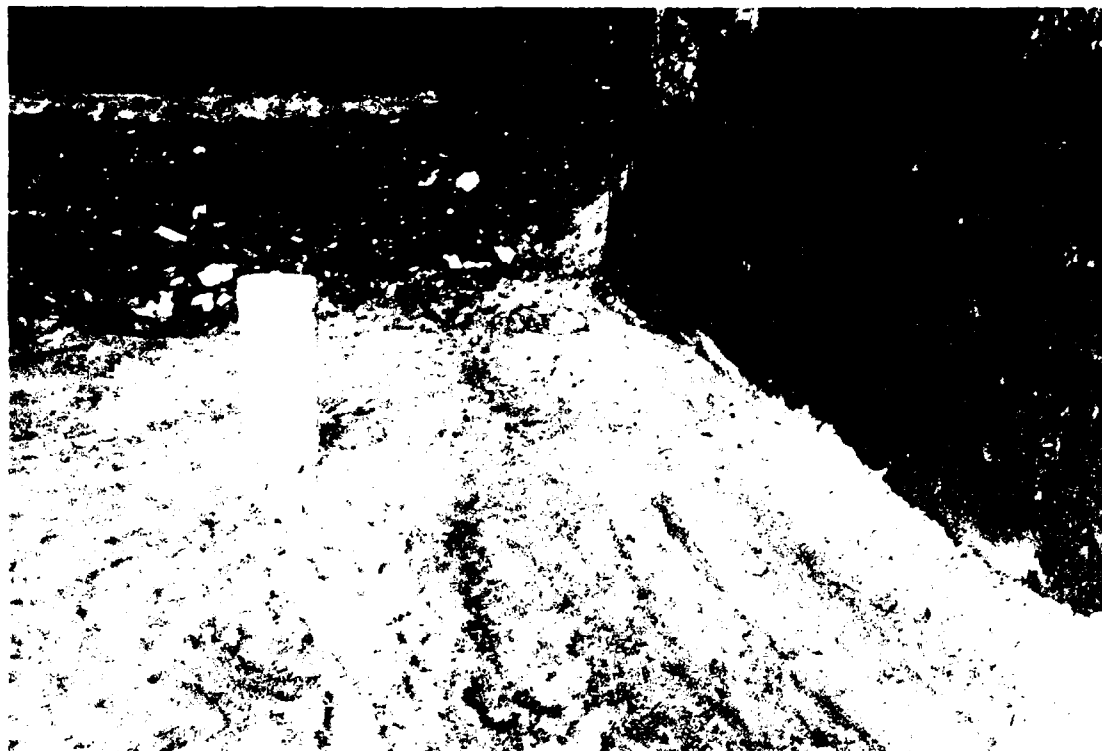


Figure 13. Bare C-4 charge in position for Test 2



Figure 14. Crater and front wall damage from C-4 detonation

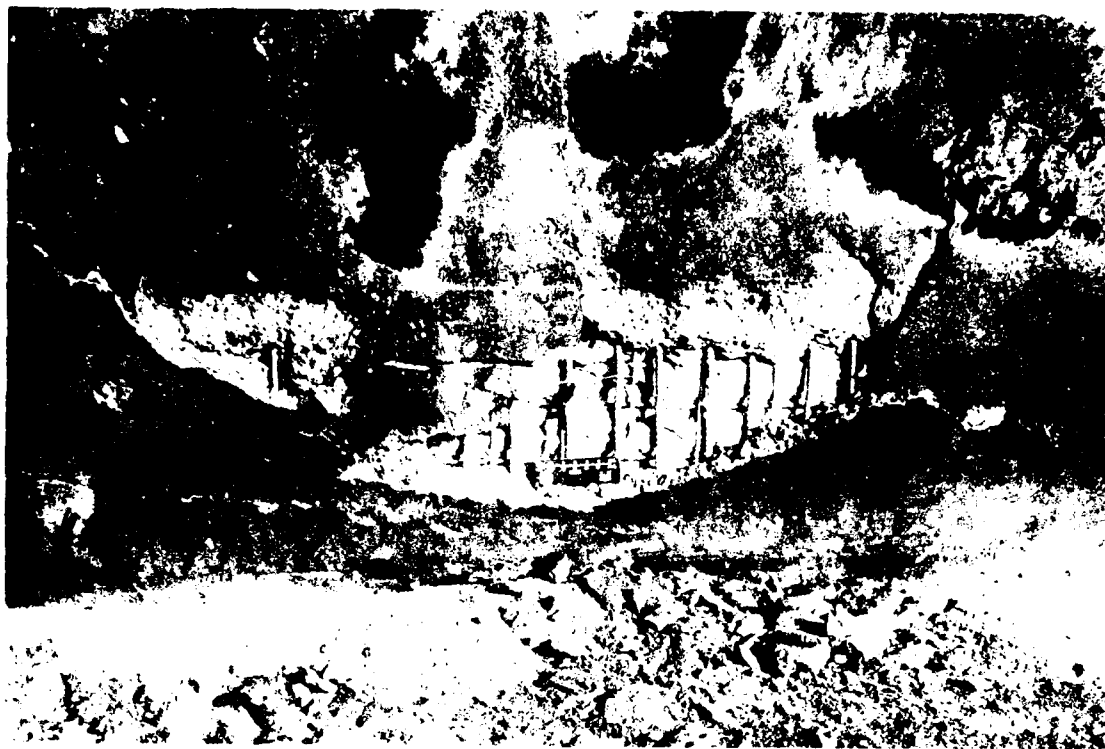


Figure 15. Close-up of damage to front of wall from Test 2

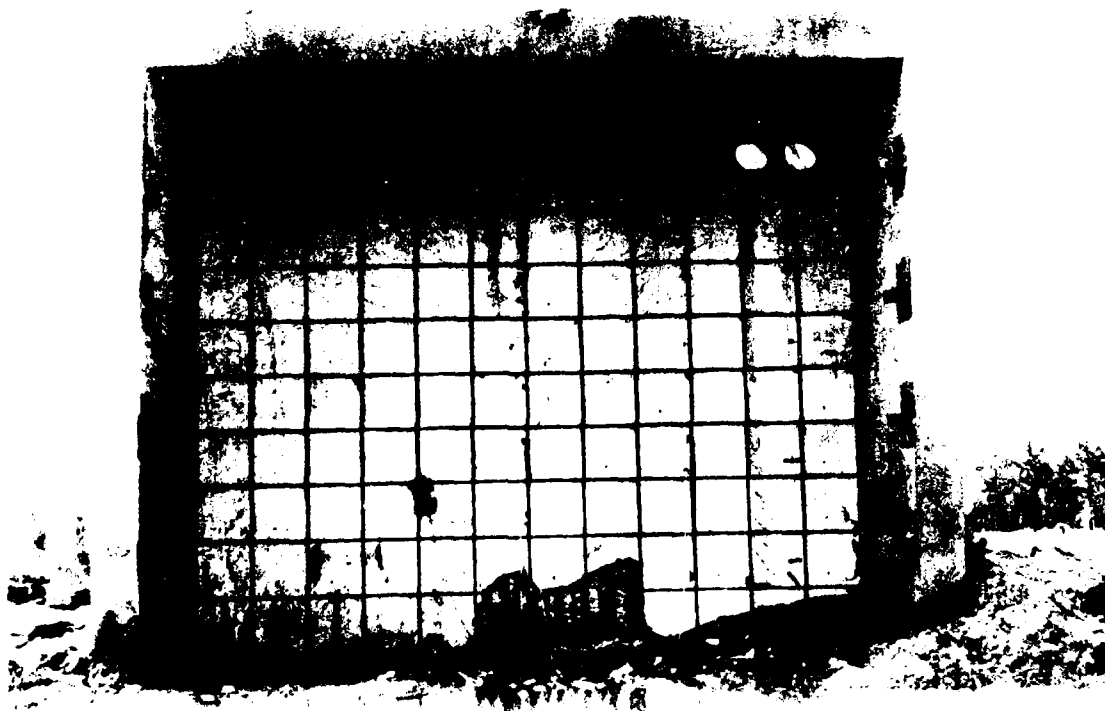


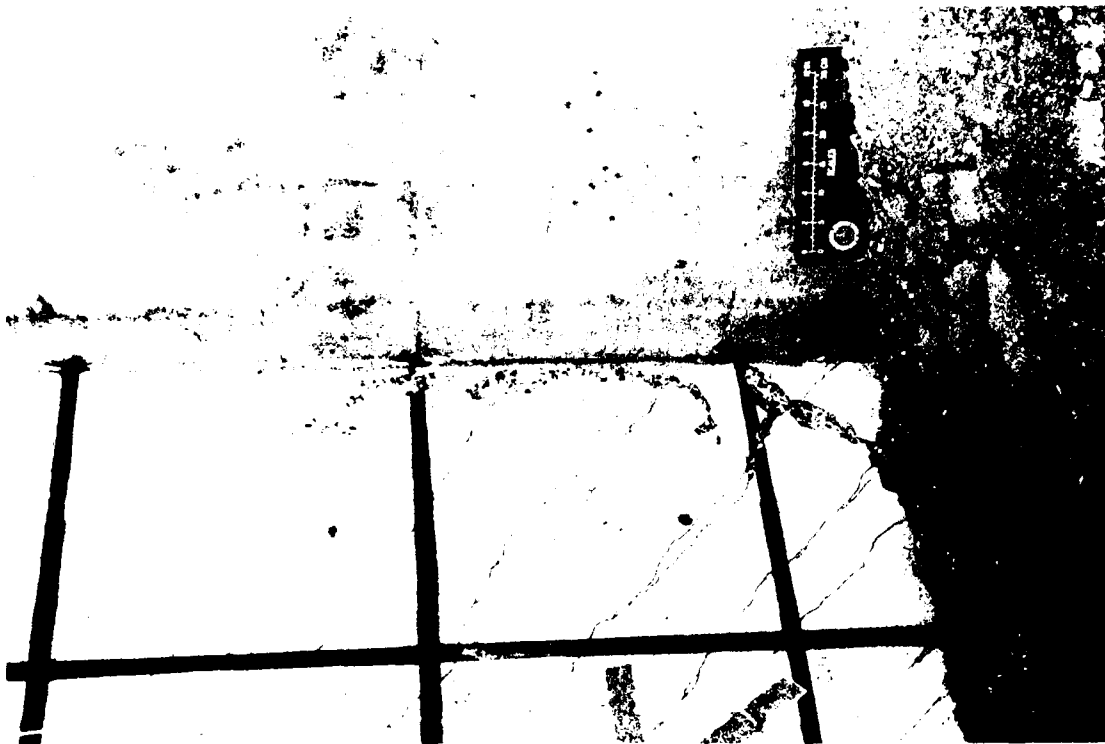
Figure 16. Overall view of damage to rear of wall from Test 2



Figure 17. Close-up of spalled area on rear of wall from Test 2



a. Intersection with test side wall



b. Intersection with right side wall

Figure 18. Cracks formed near side supports from Test 2



Figure 19. Cased TNT charge in position for Test 3



Figure 20. Crater and wall damage from cased TNT detonation

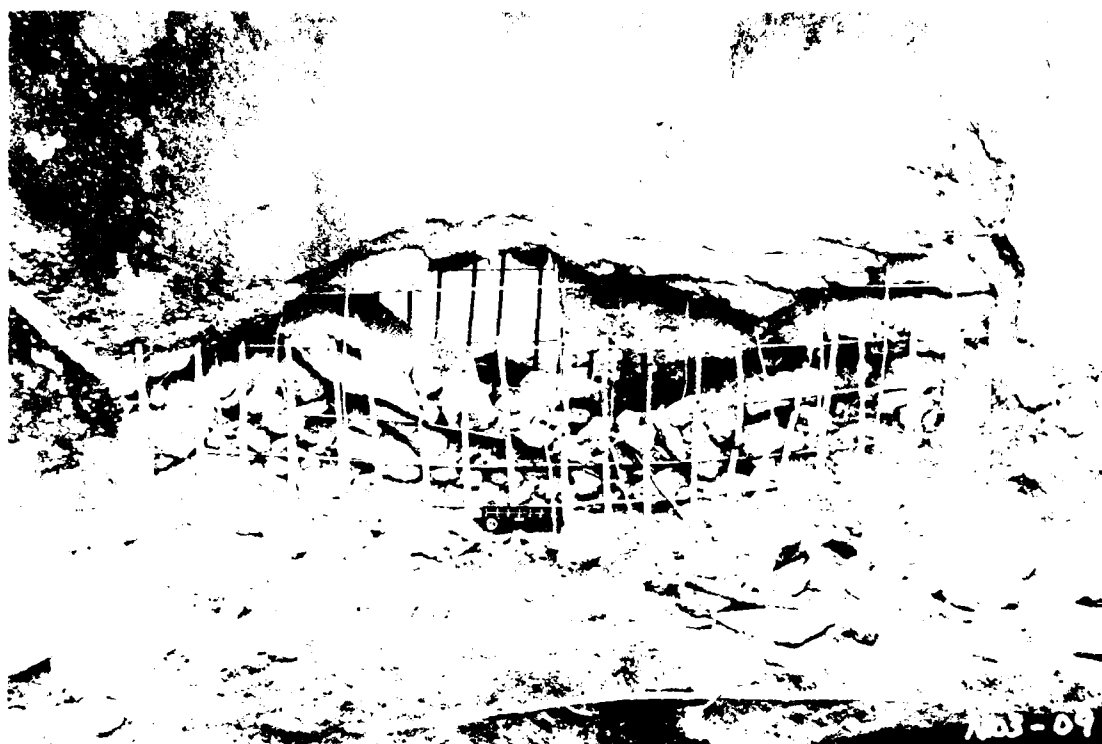


Figure 21. Close-up of breached area from Test 3



Figure 22. Damage to rear of wall from Test 3

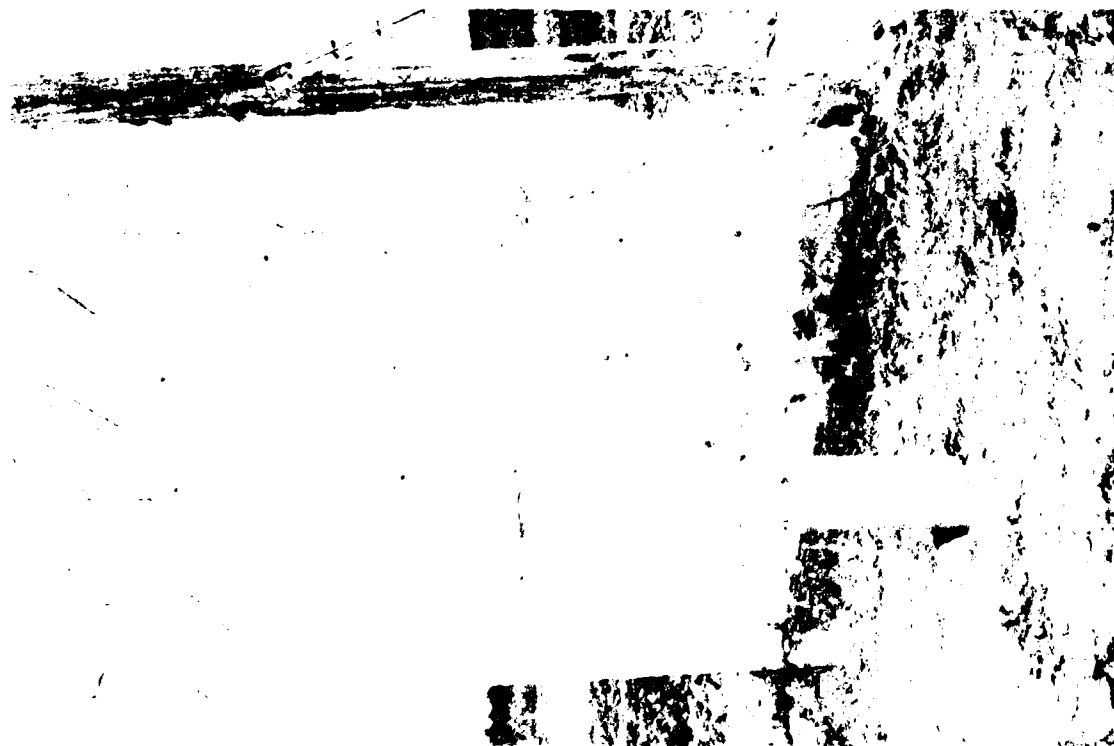


Figure 23. Bare TNT charge in position for Test 4



Figure 24. Damage to outside of wall from Test 4



Figure 25. Damage to inside of wall from Test 4



Figure 26. Close-up of bottom of wall showing extent of permanent deflection



Figure 27. Cased TNT charge in position for Test 5



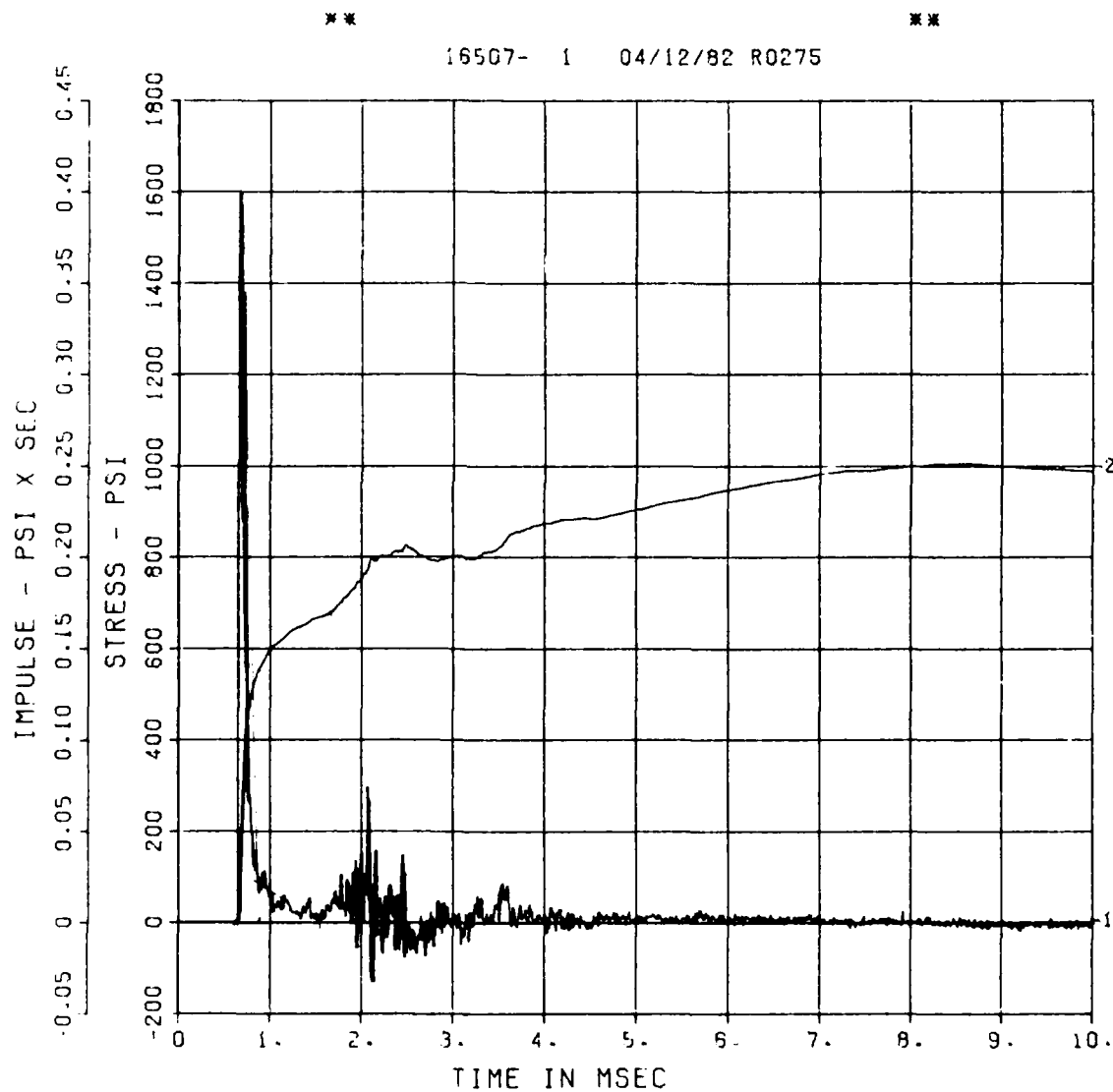
Figure 28. Damage to outside of wall from Test 5
and fragment impact from the cased TNT



Figure 29. Damage to inside of wall from Test 5

APPENDIX A
BLAST PRESSURE DATA

DHF BARE TNT
IOP
200000. HZ CAL= 1379.

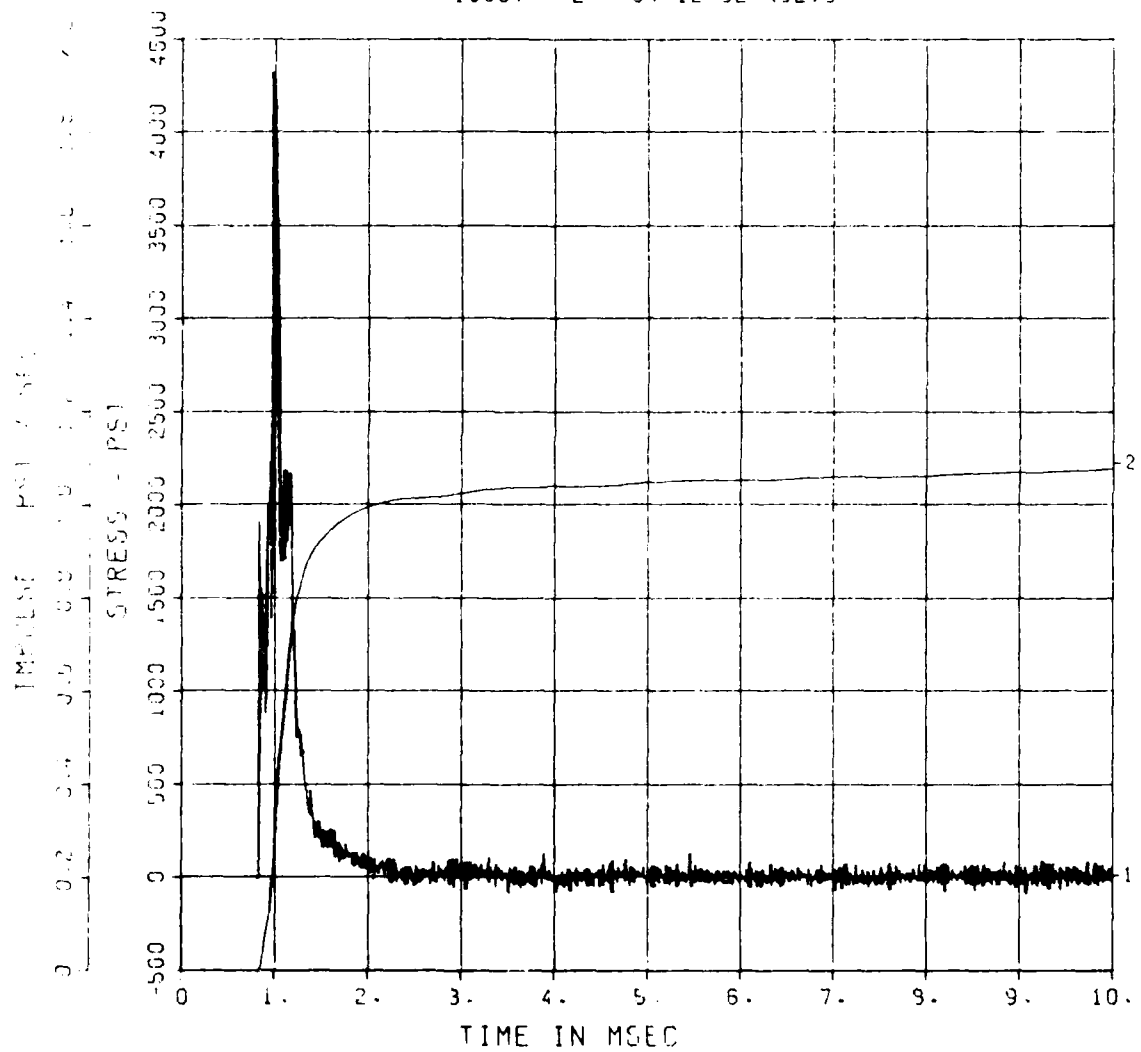


** PEAK VALUE IS 16 % OVER CALIBRATION **

DHF BARE INT
PMI

200000. HZ CAL= 7300.

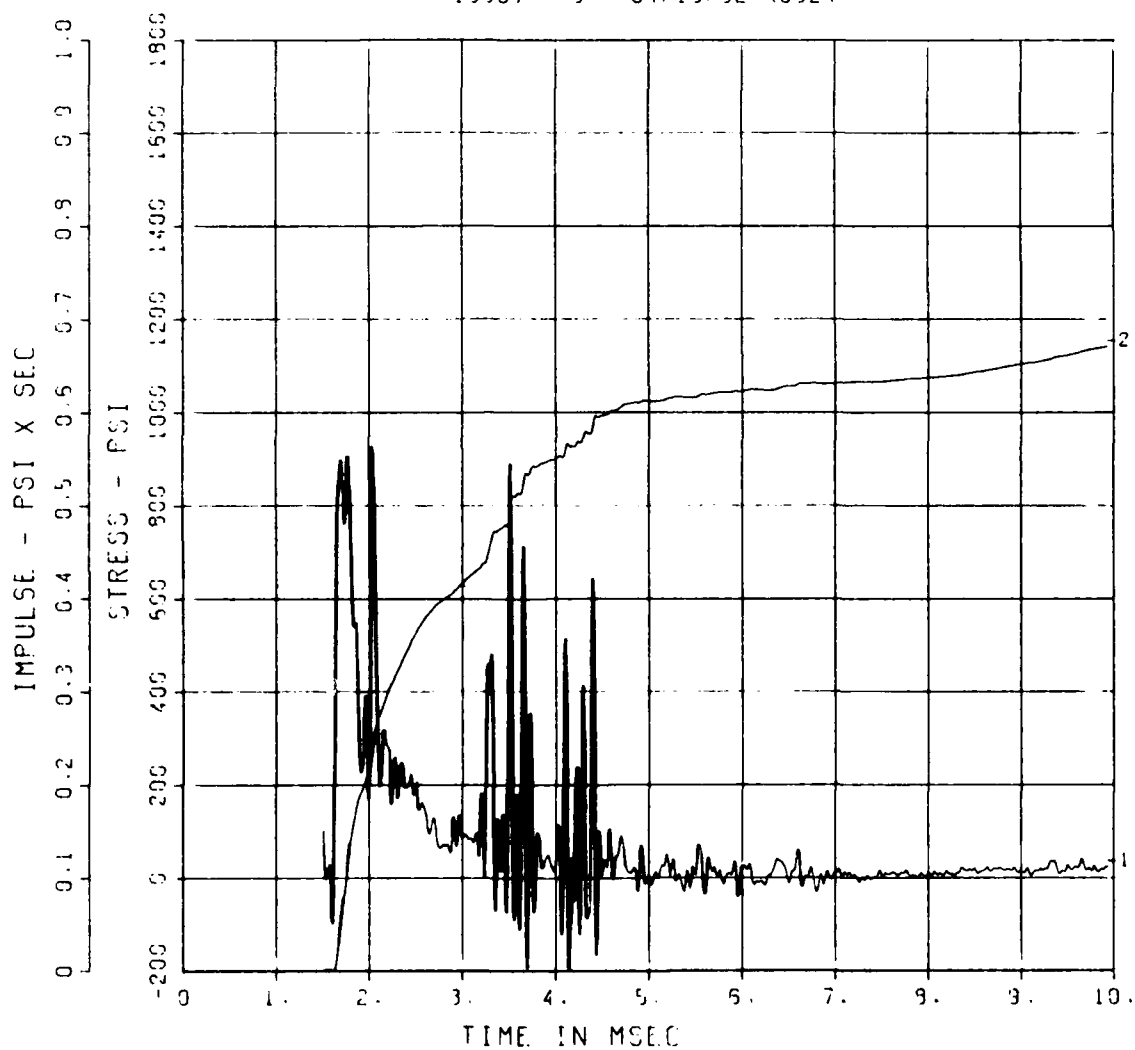
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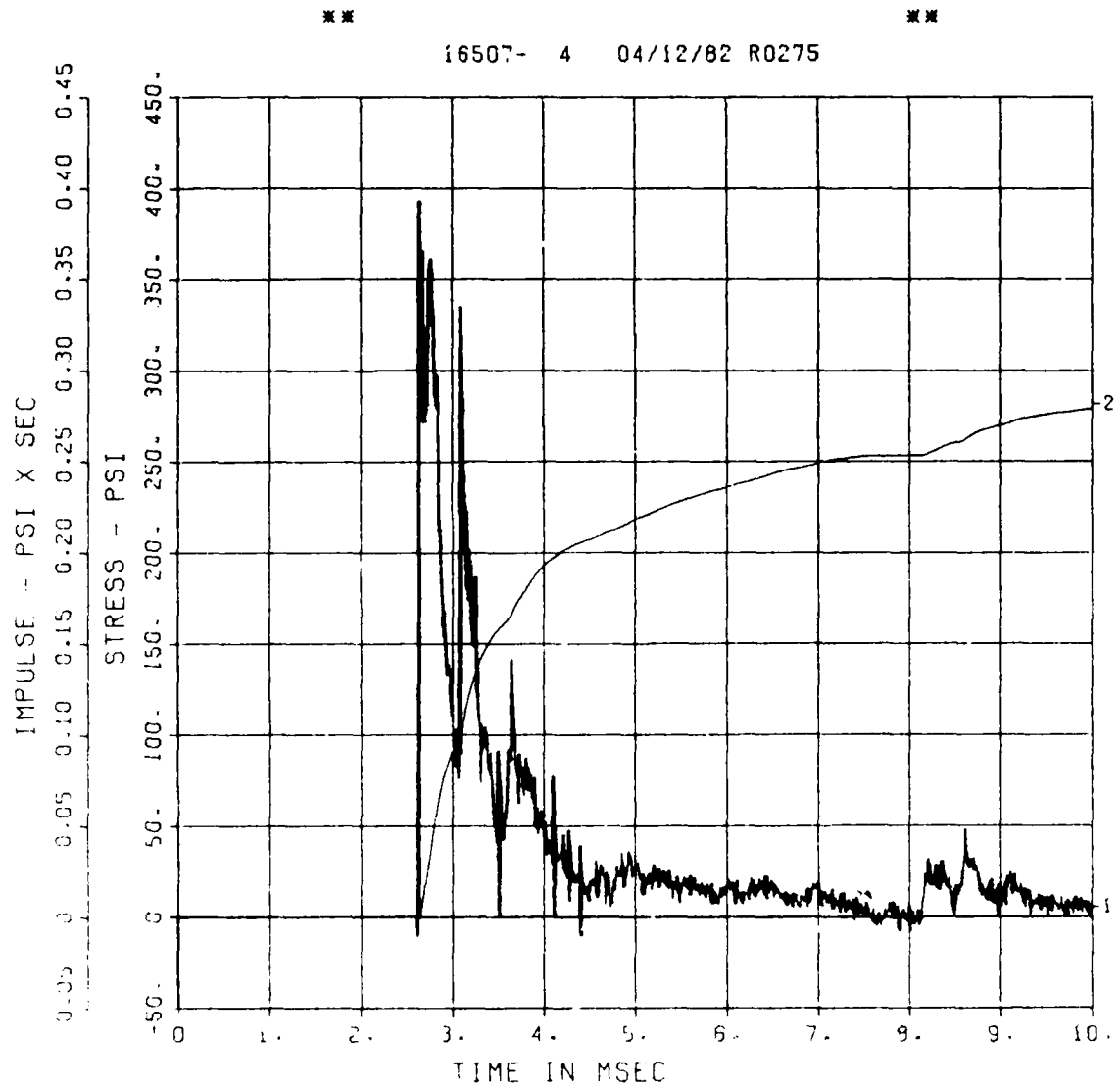
DHF BARE INT
PM2

200000 HZ CAL= 1375.
LP2 70% CUTOFF= 18000. HZ

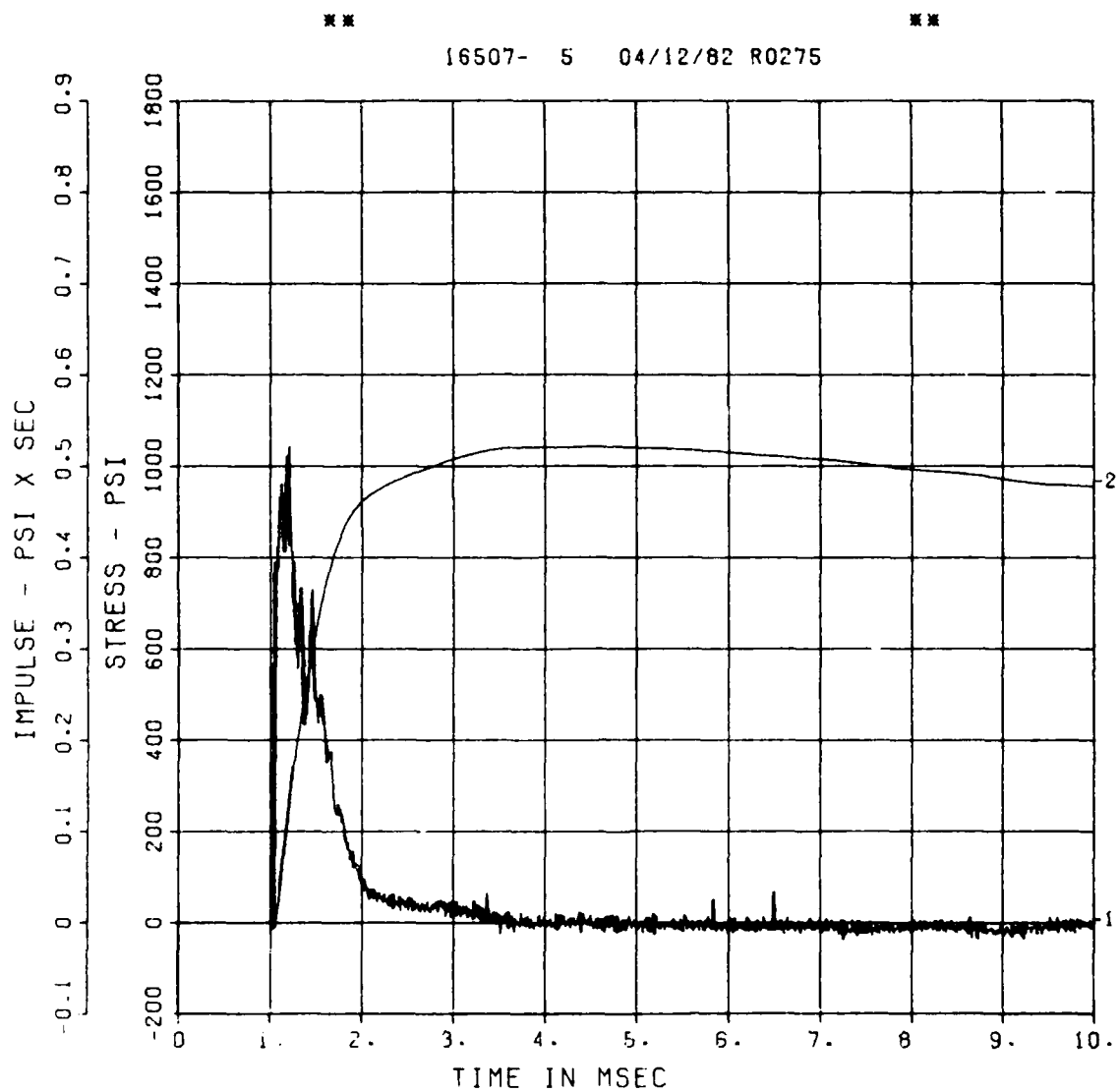
16007- 3 04/13/92 R0321



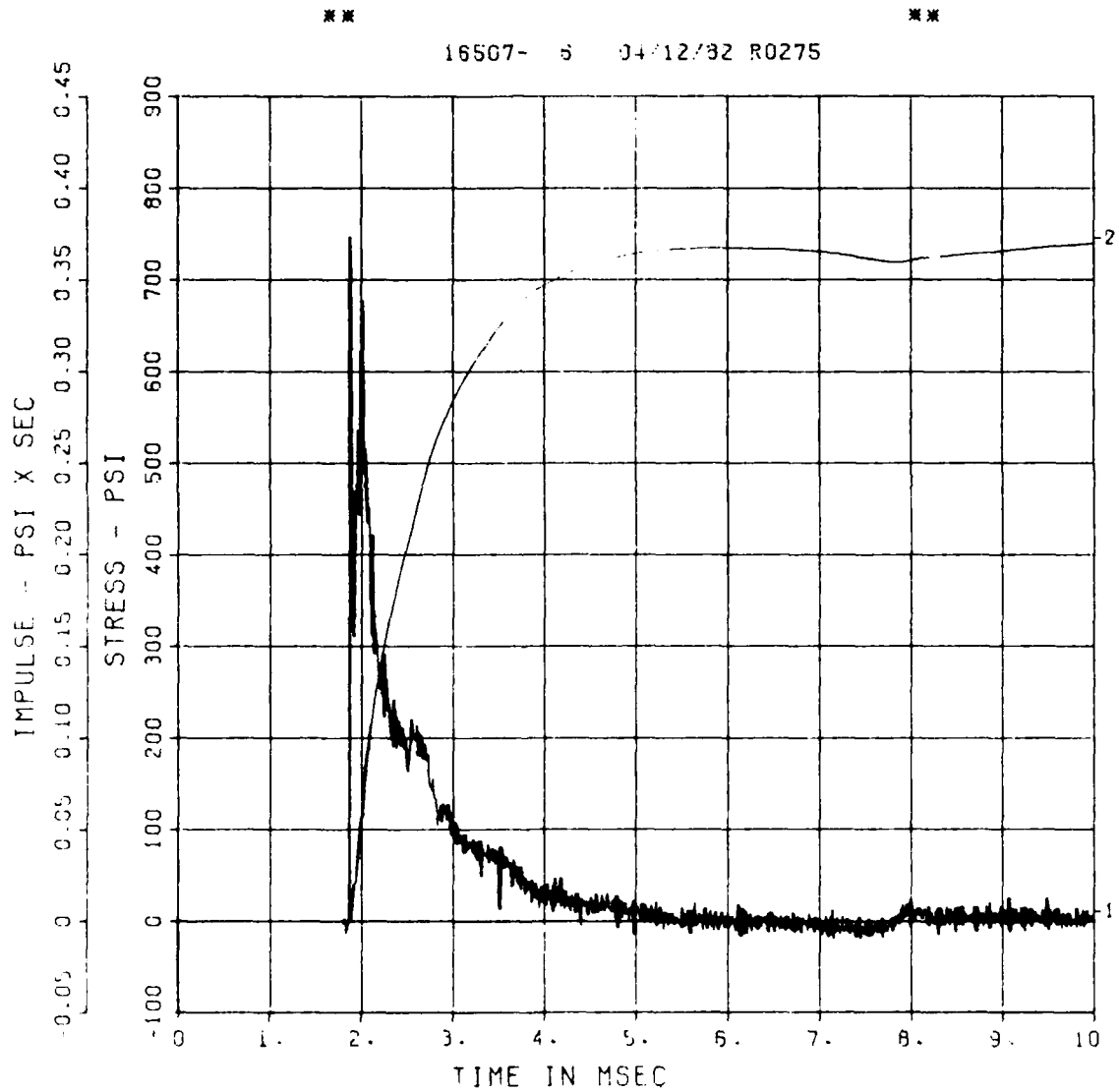
DHF BARE TNT
PM3
200000. HZ CAL= 682.2



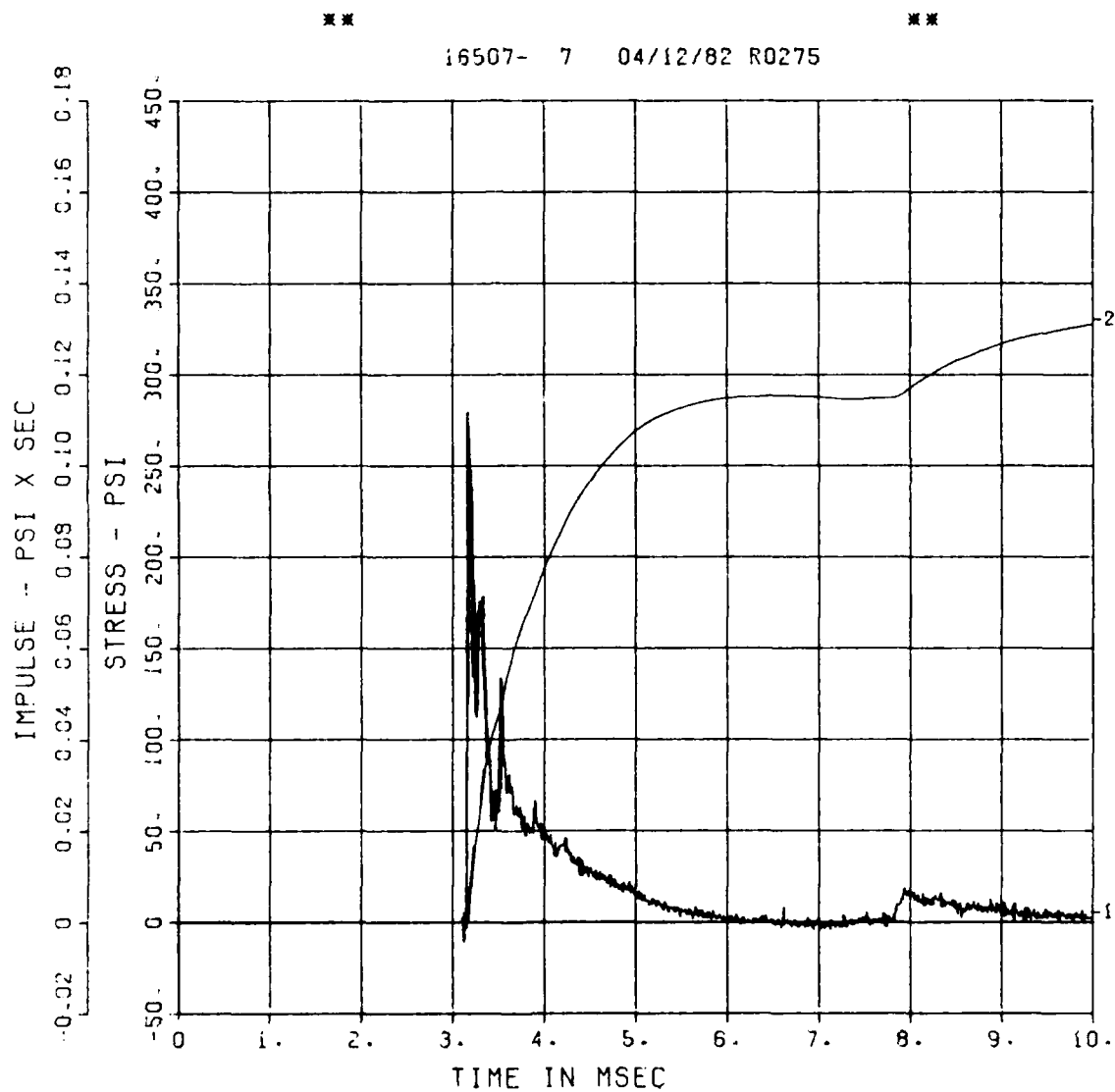
DHF BARE TNT
PQ1
200000. HZ CAL= 2815.



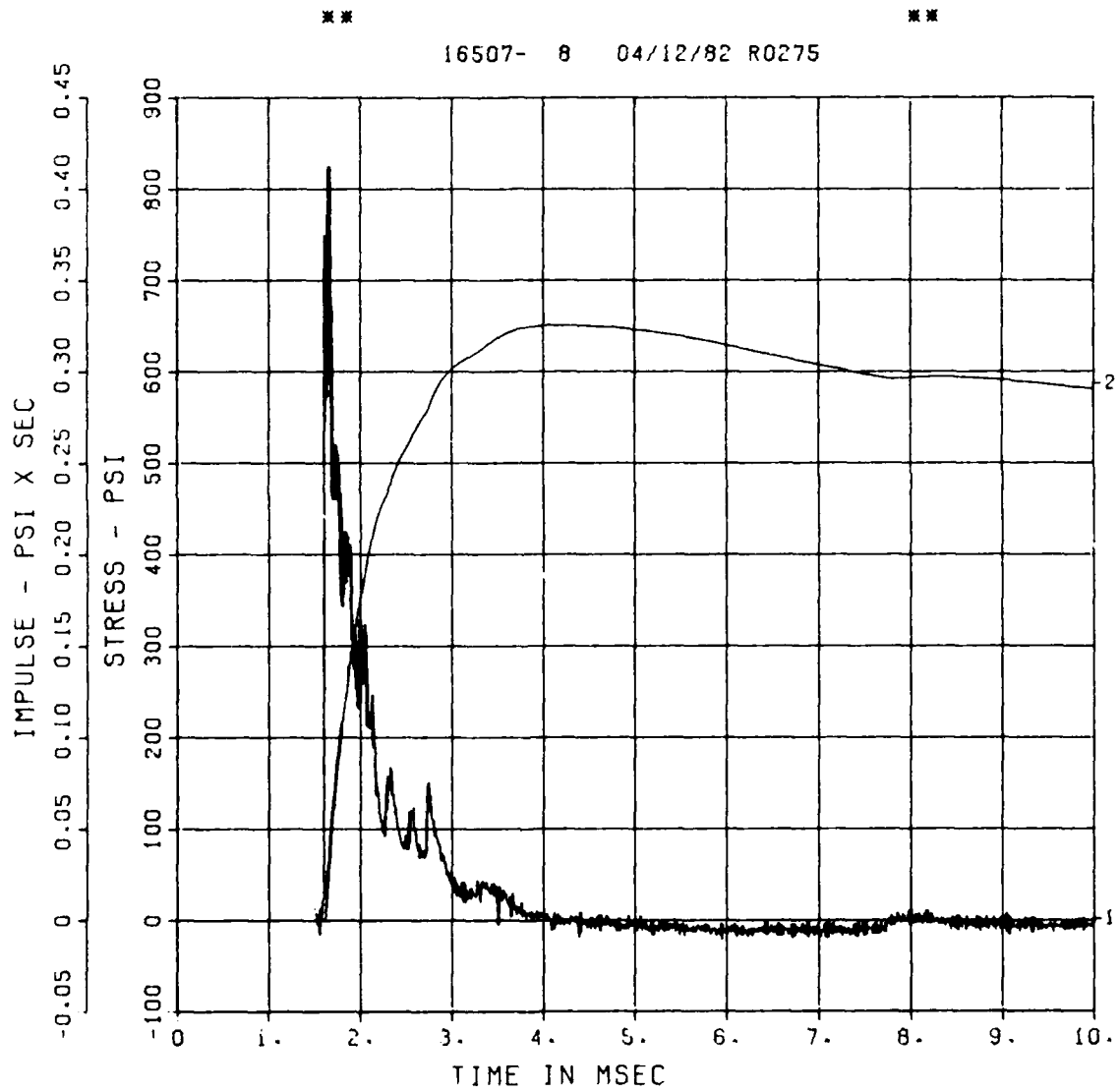
DHF BARE TNT
PQ2
200000. HZ CAL= 1309.



DHF BARE TNT
PQ3
200000. HZ CAL= 493.0



DHF BARE TNT
PS1
200000. HZ CAL= 830.0

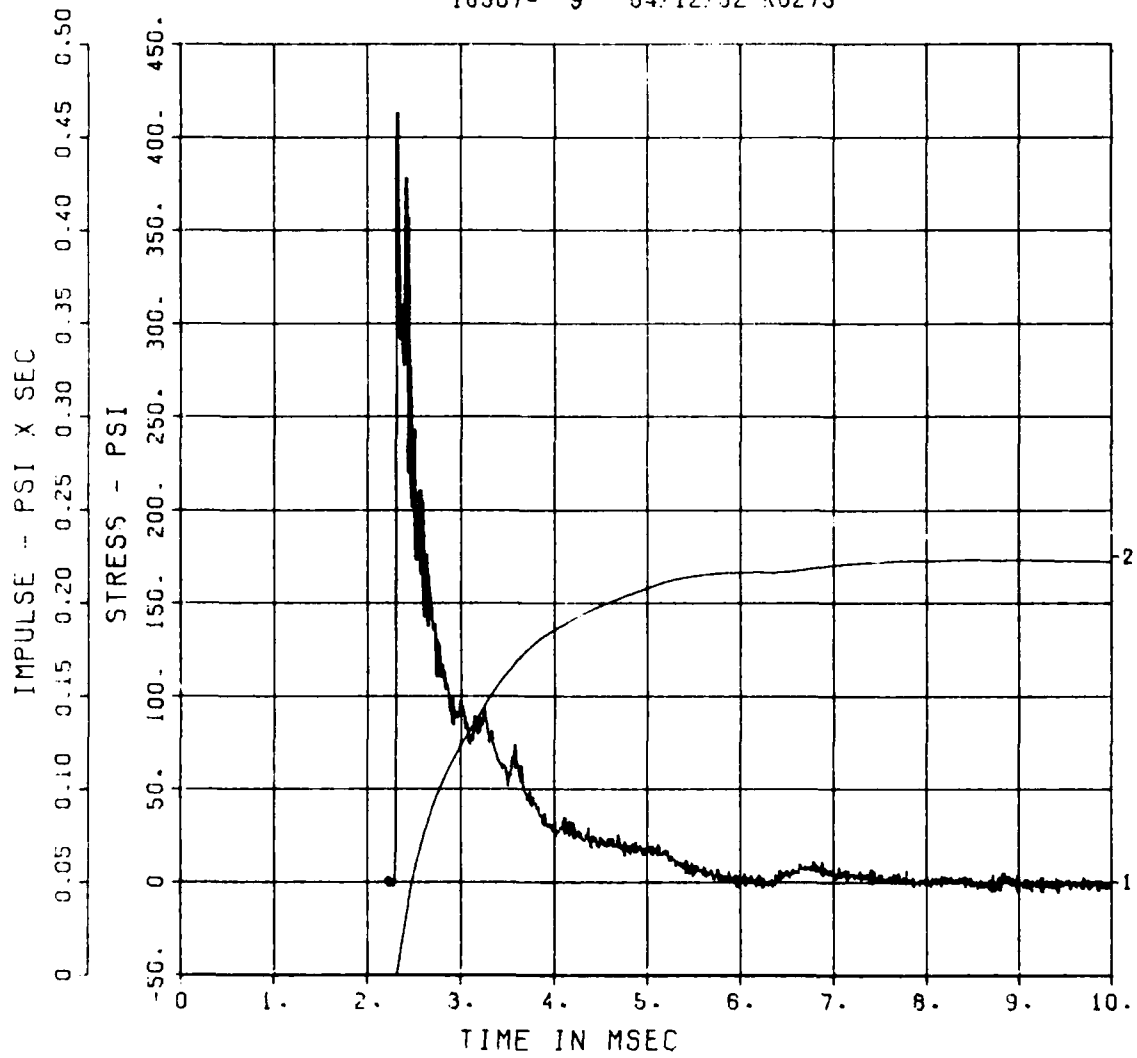


DHF BARE TNT
PS2
200000. HZ CAL= 550.0

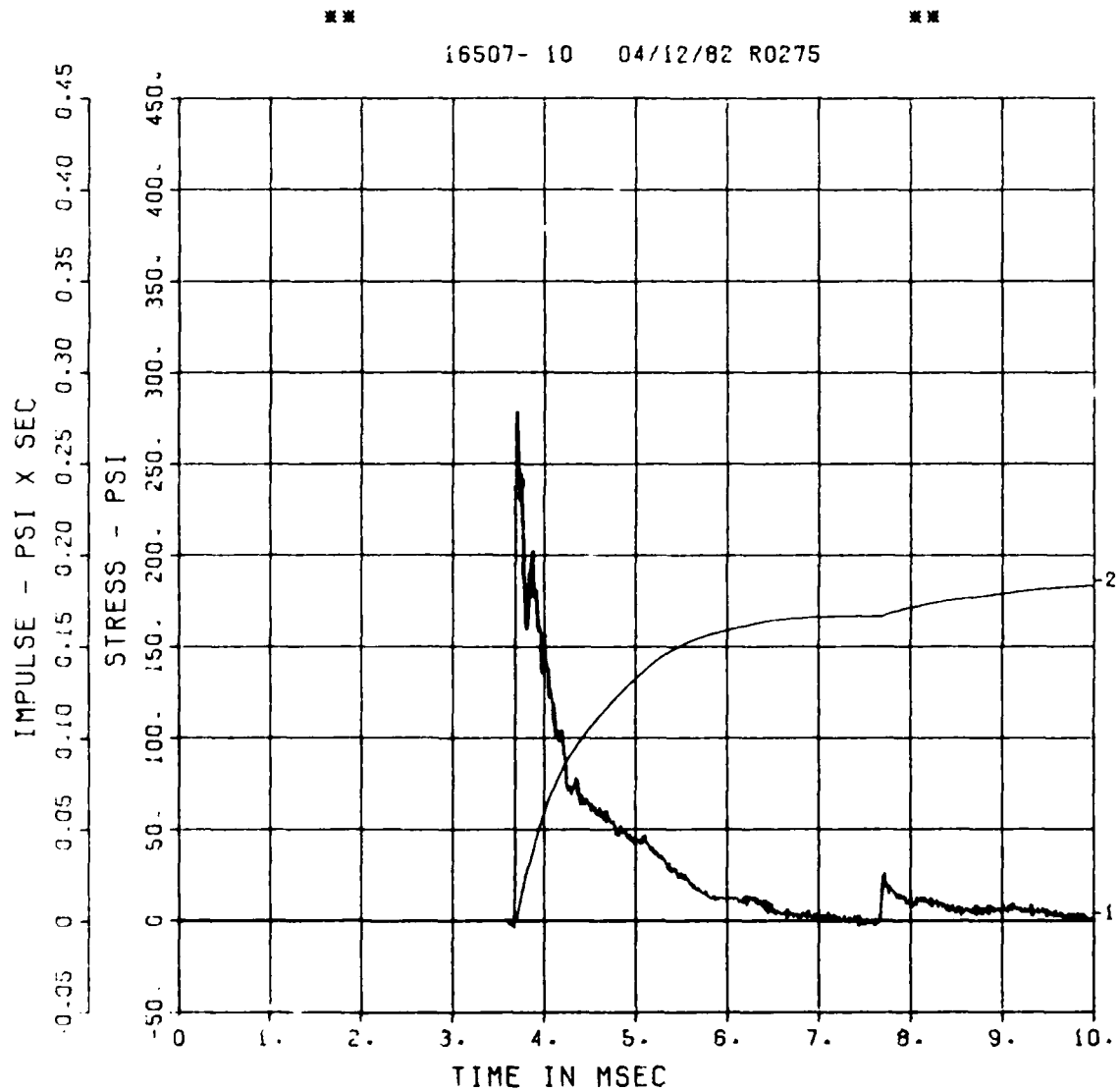
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16507- 9 04/12/92 R0275

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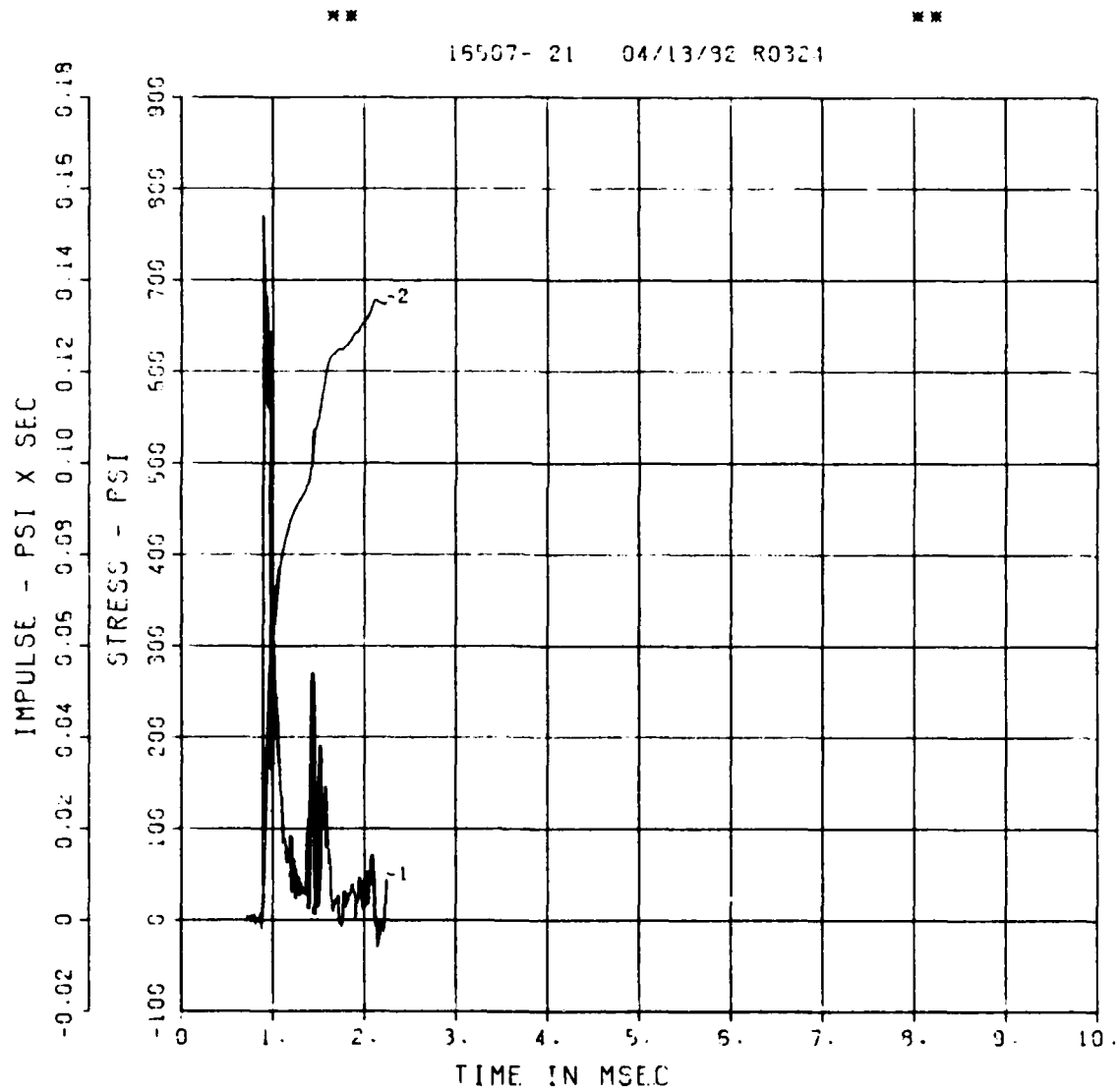


DHF BARE TNT
PS3
200000. HZ CAL= 272.0

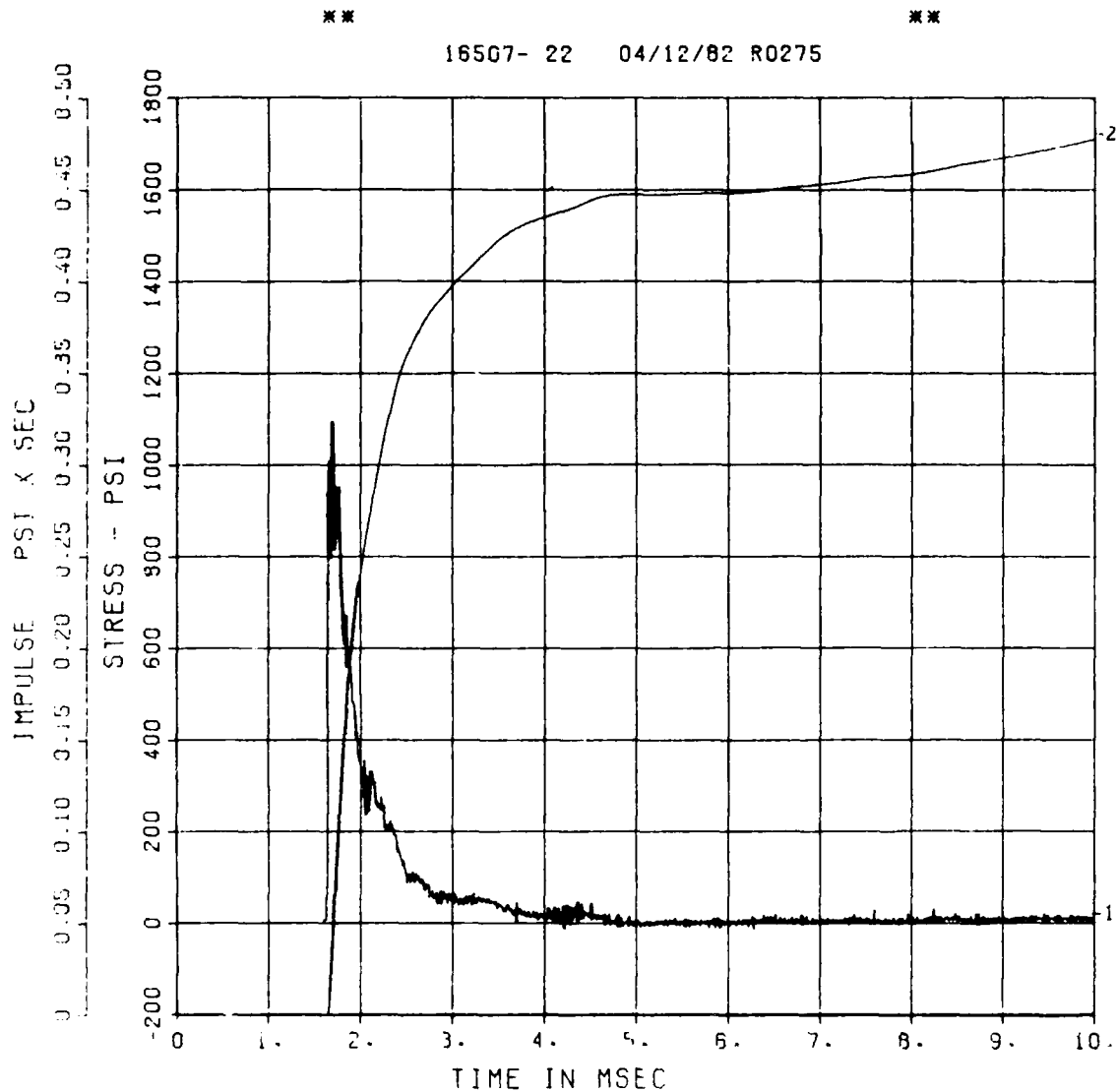


▲▲ PEAK VALUE IS 2 % OVER CALIBRATION ▲▲

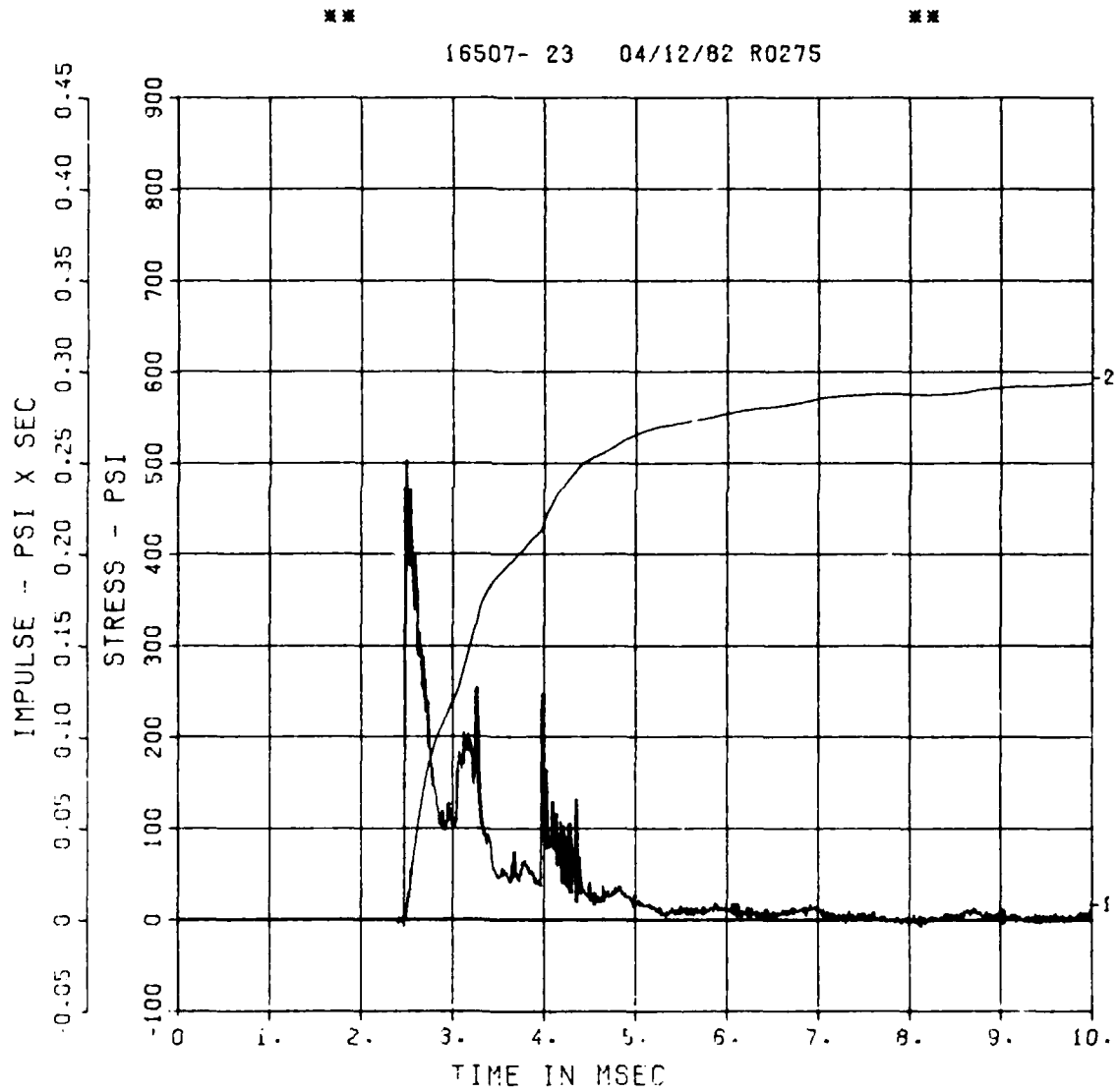
DHF CASED TNT
IOP
200000. HZ CAL= 1179.



DHF CASED TNT
PM2
200000. HZ CAL= 1493.

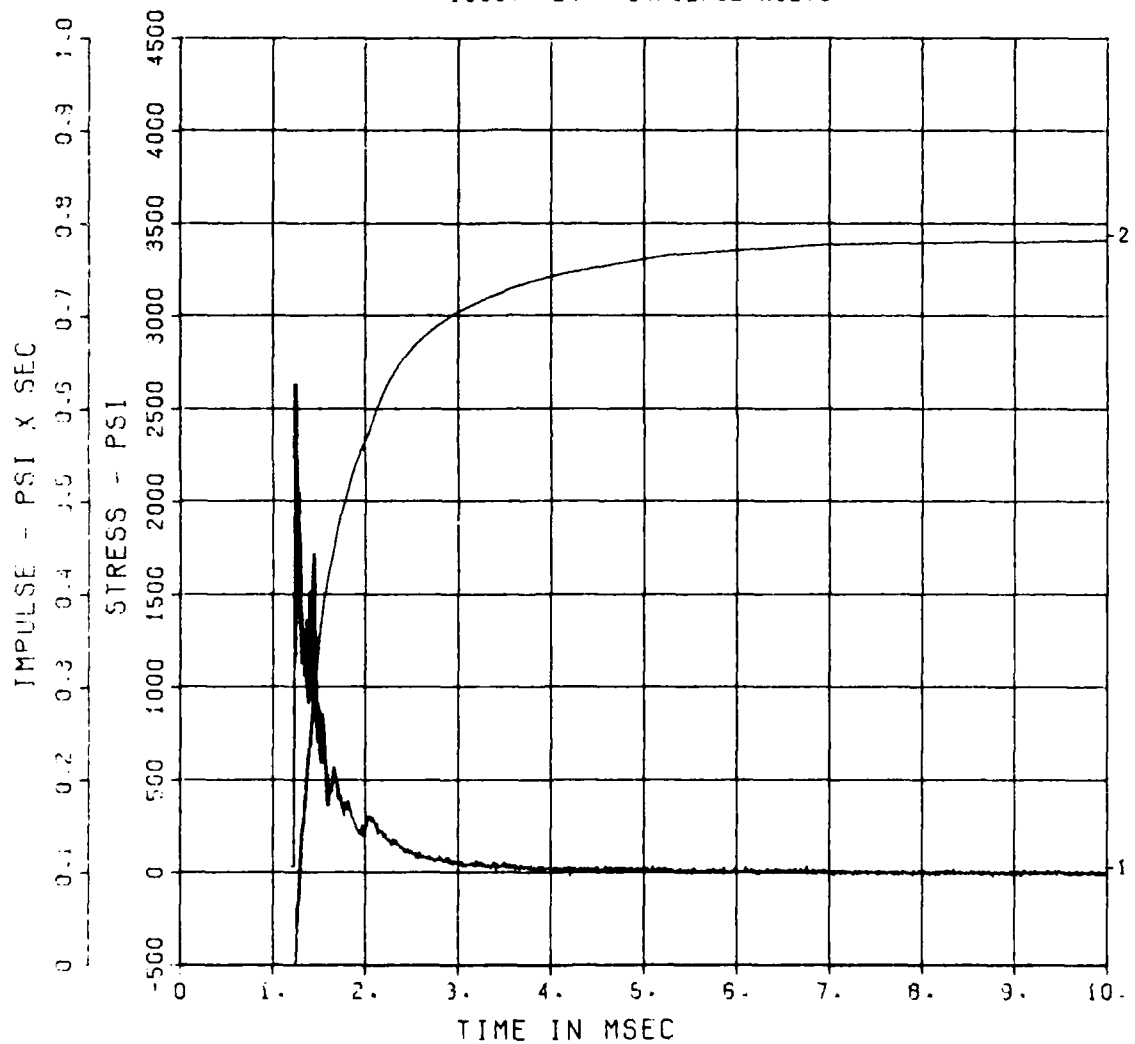


DHF CASED TNT
PM3
200000. HZ CAL= 682.2

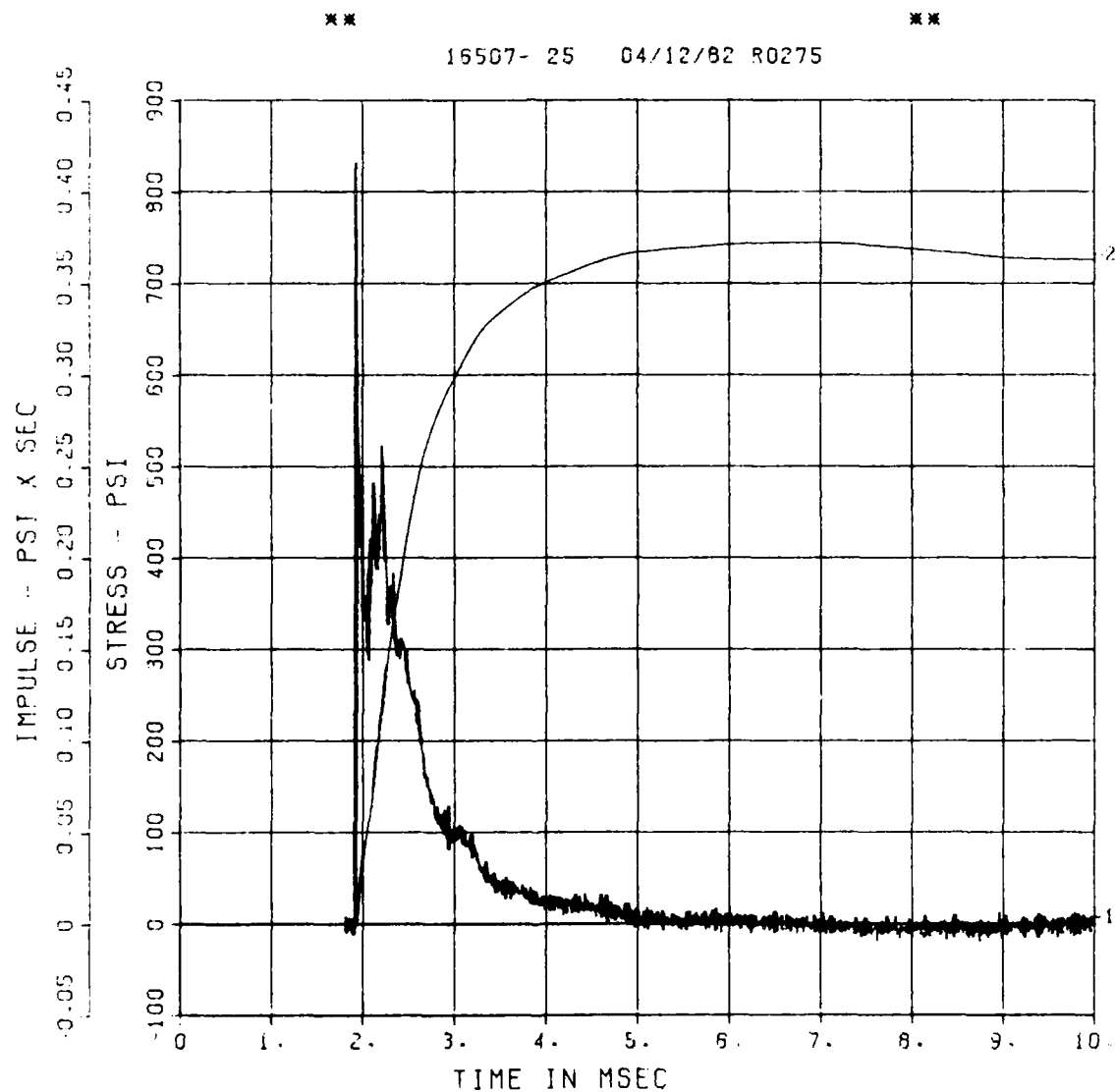


DHF CASED TNT
PQ1
200000. HZ CAL= 2815.

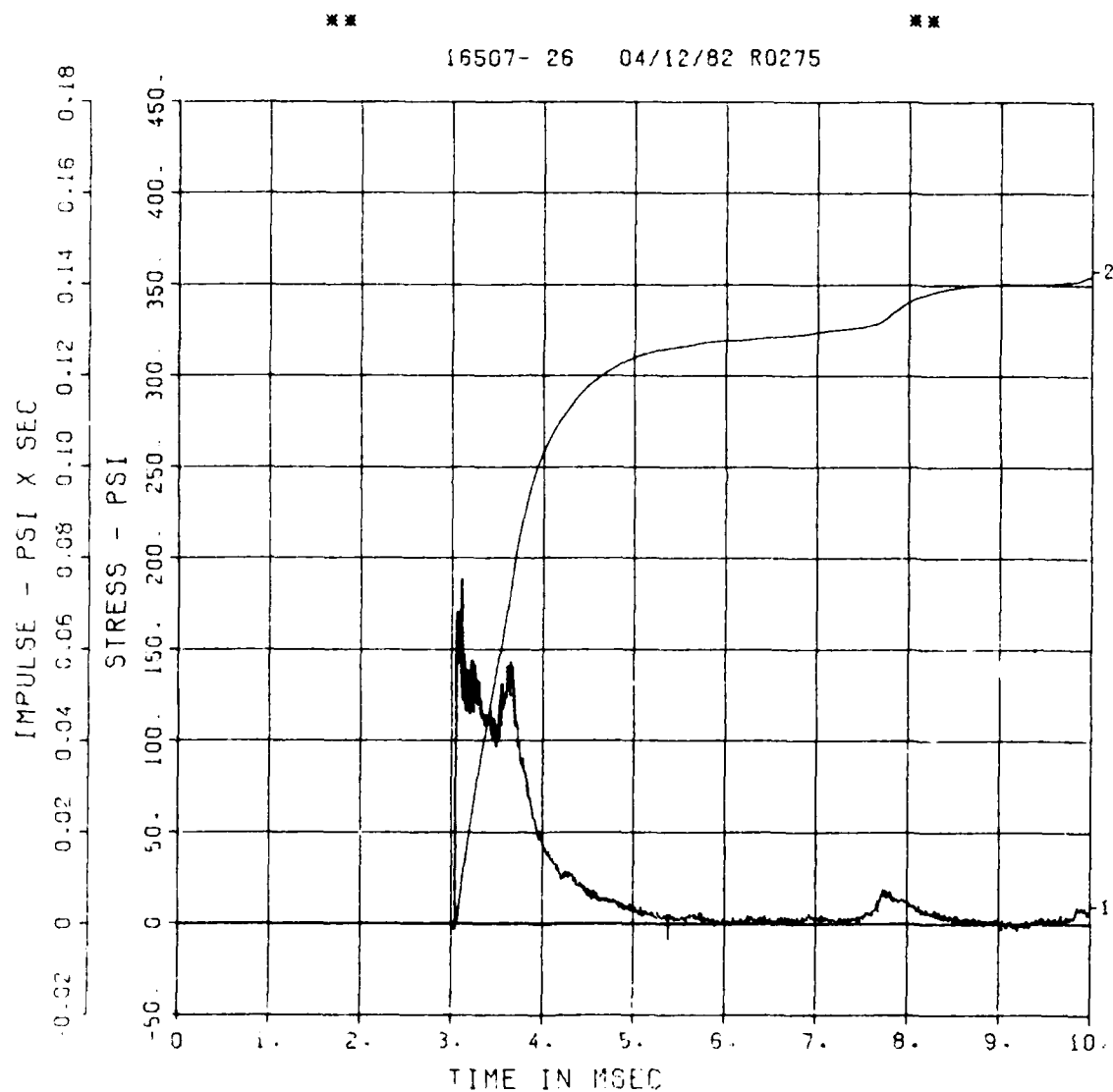
16507- 24 04/12/82 R0275



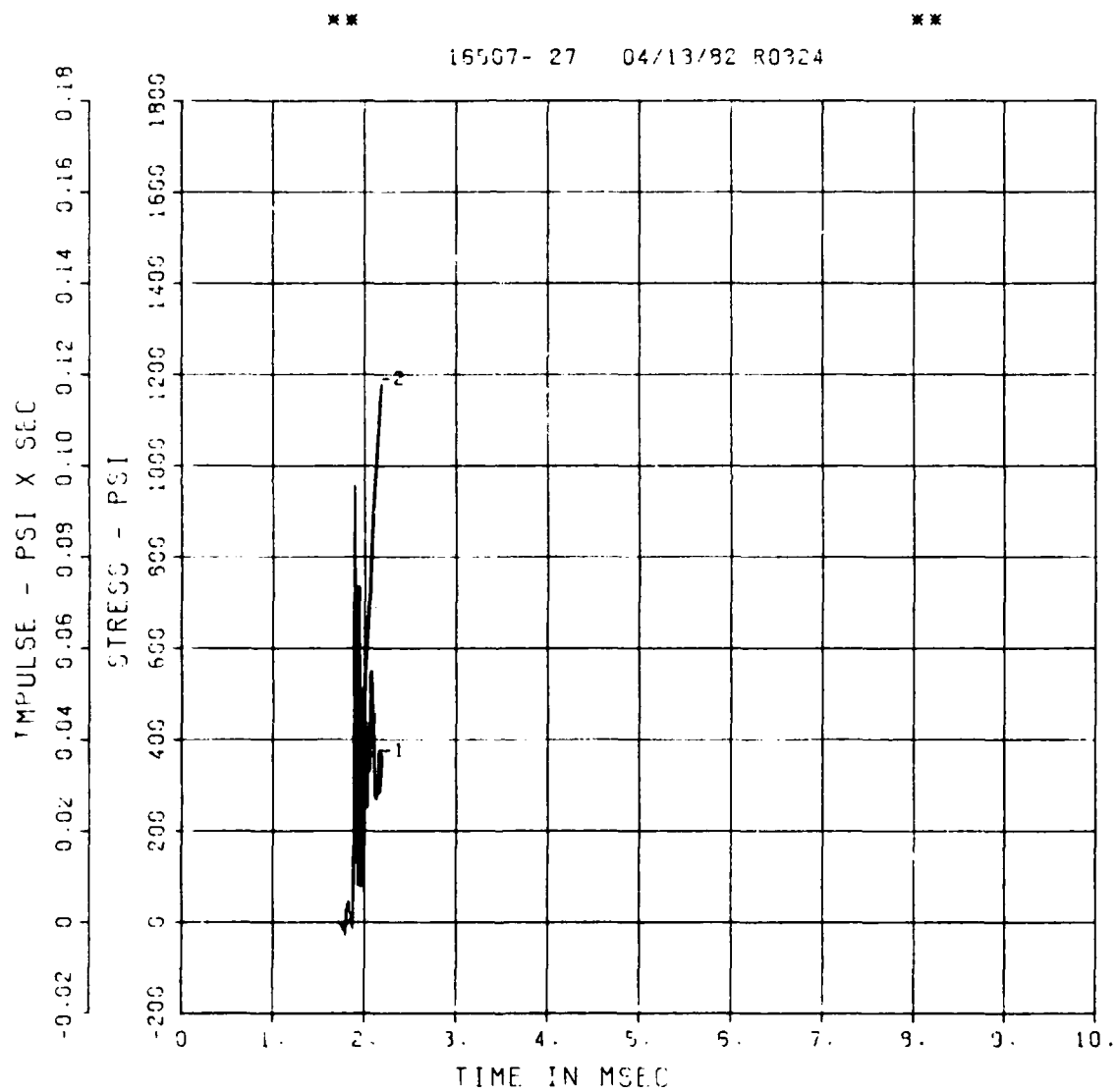
DHF CASED TNT
PQ2
200000. HZ CAL= 1309.



DHF CASED TNT
PQ3
200000. HZ CAL= 493.0

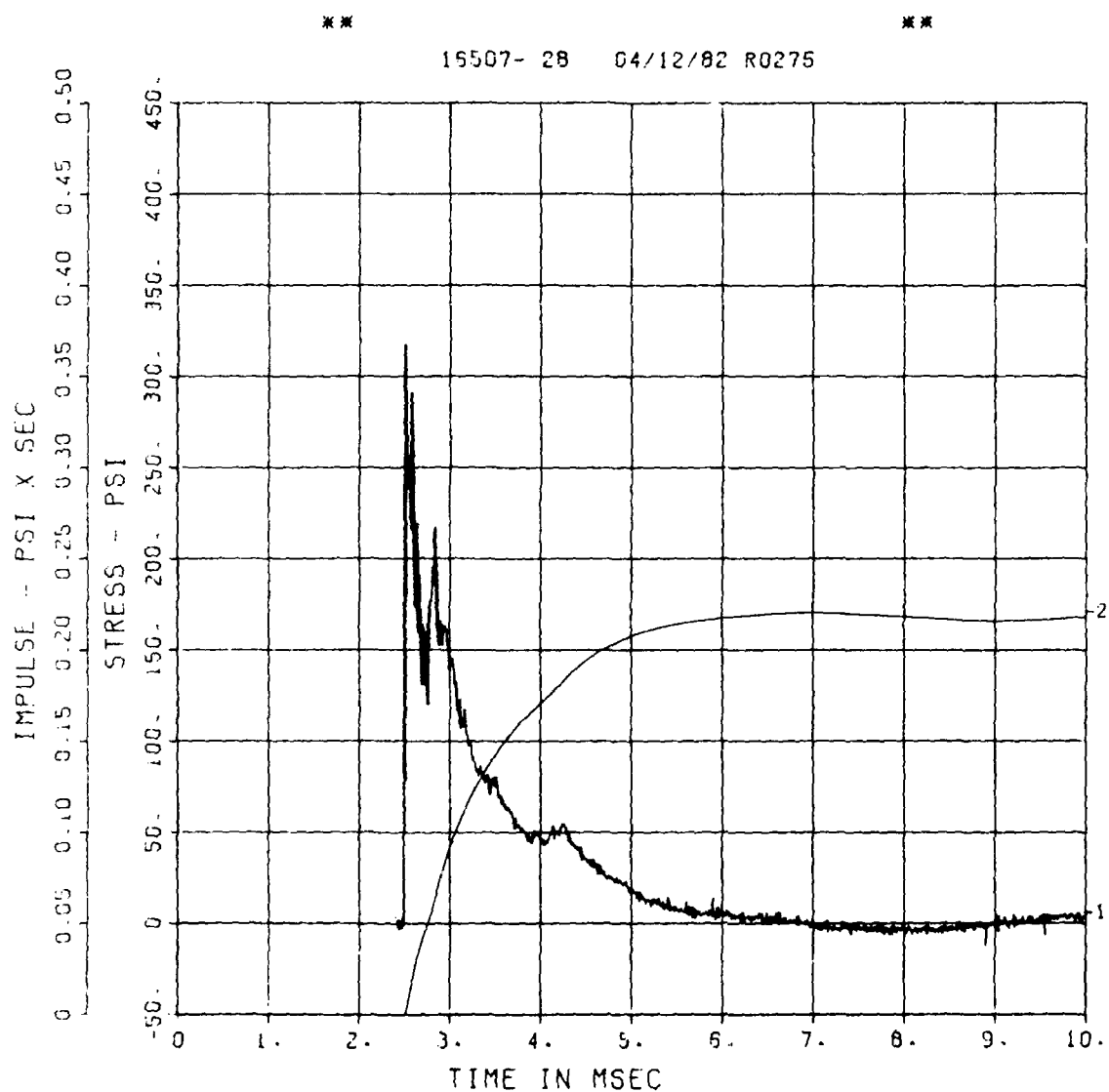


DHF CASED TNT
PS1
200000. HZ CAL= 830.0

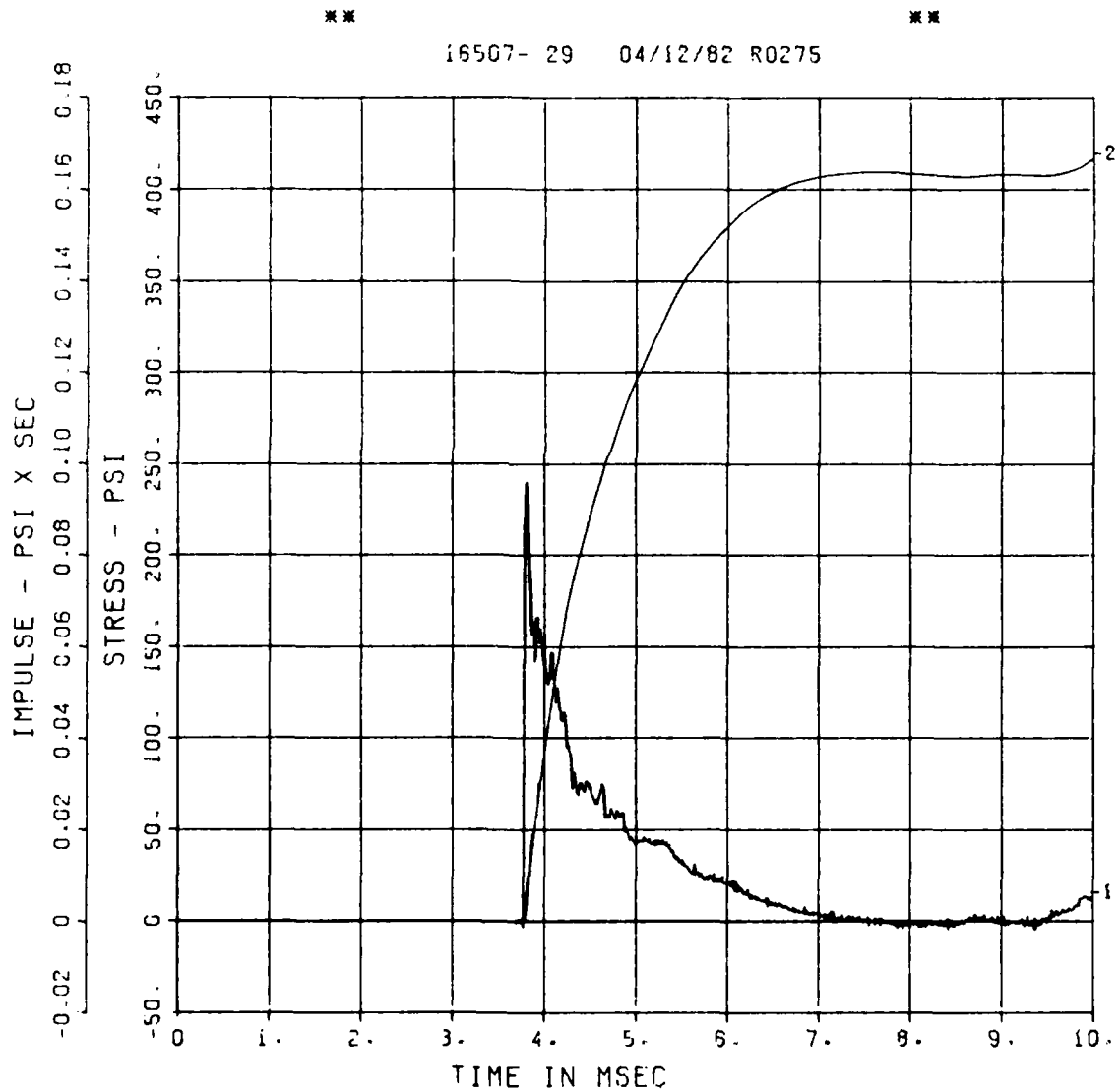


■ PEAK VALUE IS 15 % OVER CALIBRATION ■

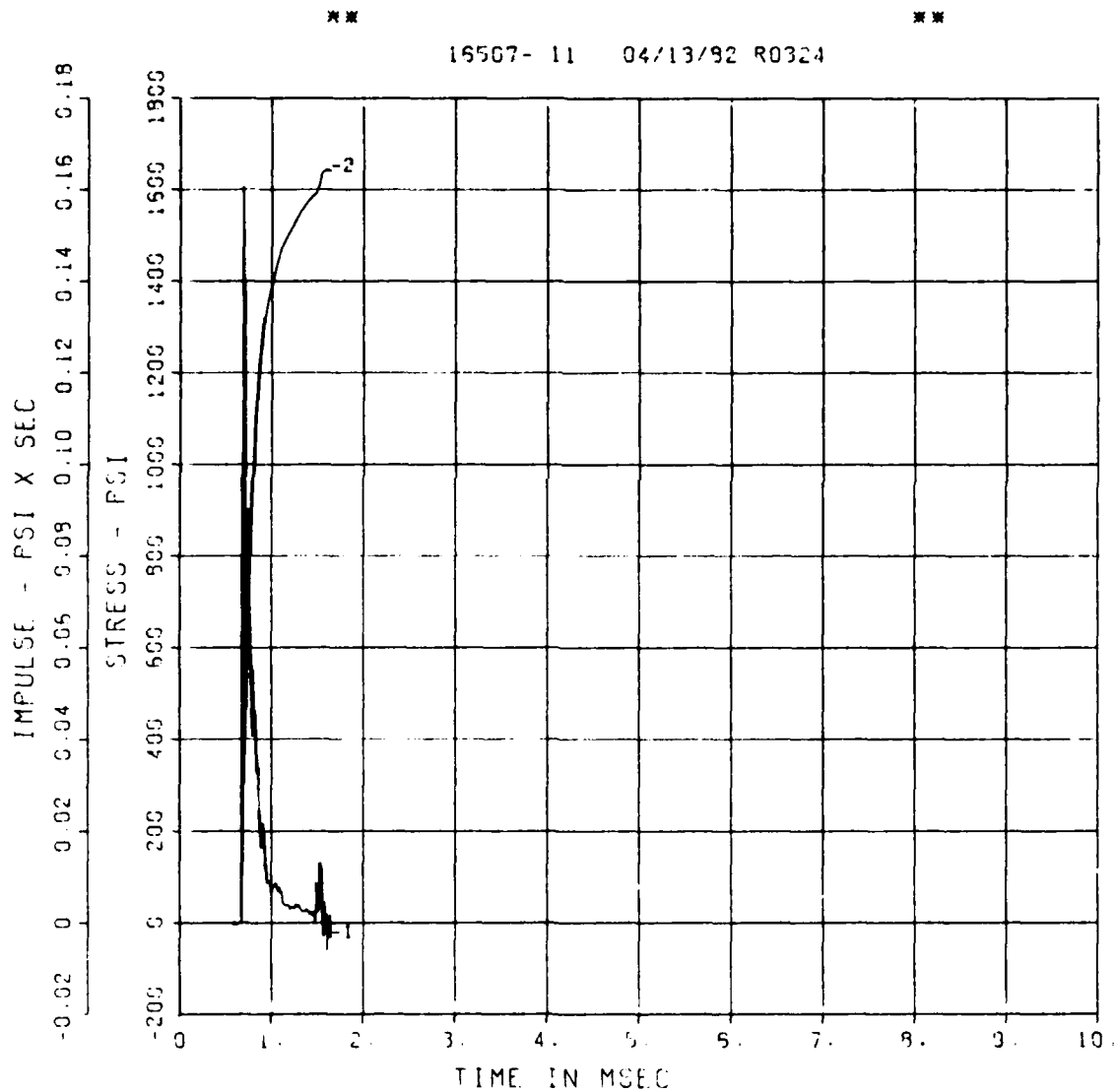
DHF CASED TNT
PS2
200000. HZ CAL= 550.0



DHF CASED TNT
PS3
200000. HZ CAL= 272.0

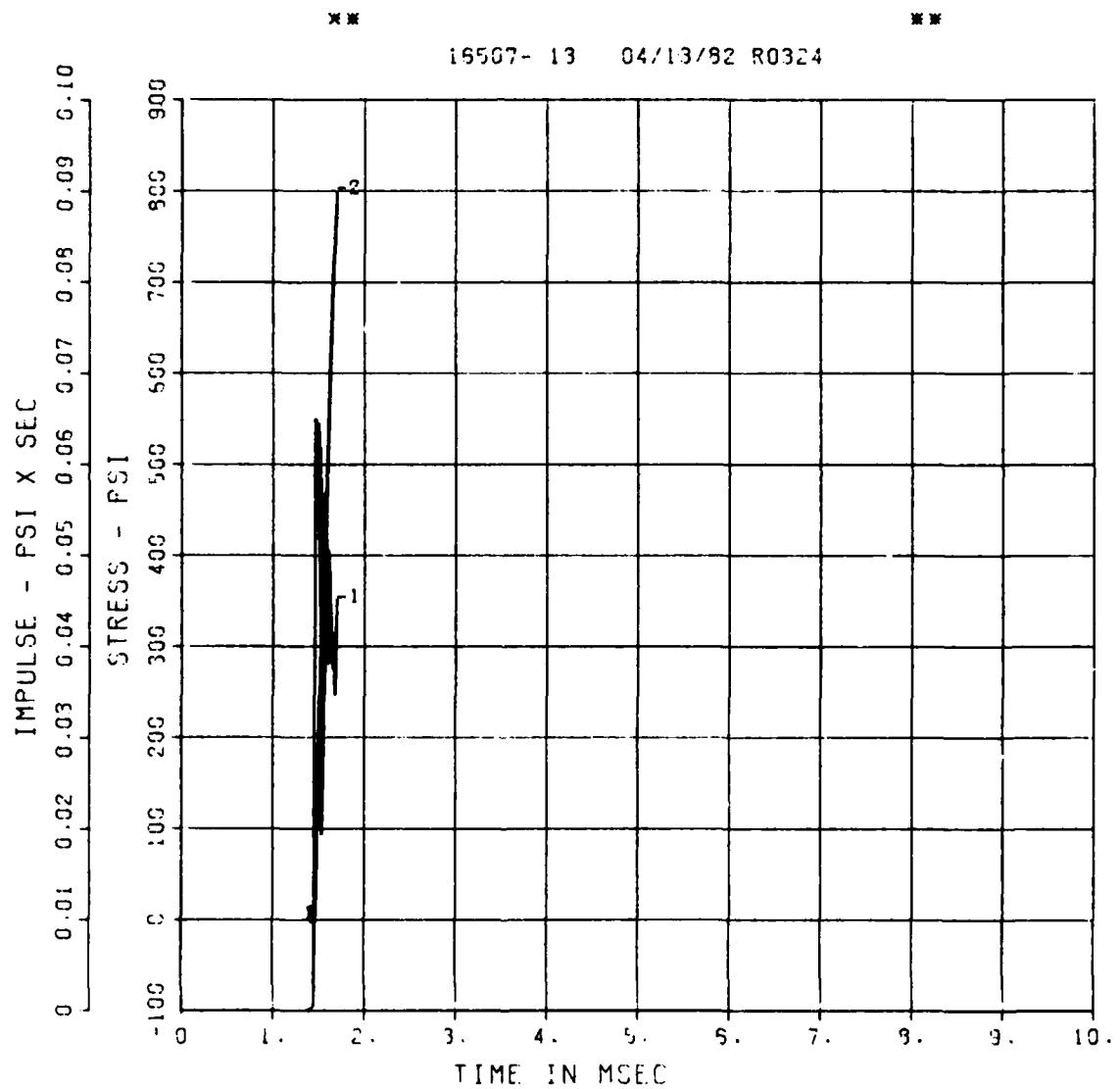


DHF BARE C4
IOP
200000. HZ CAL= 1379.

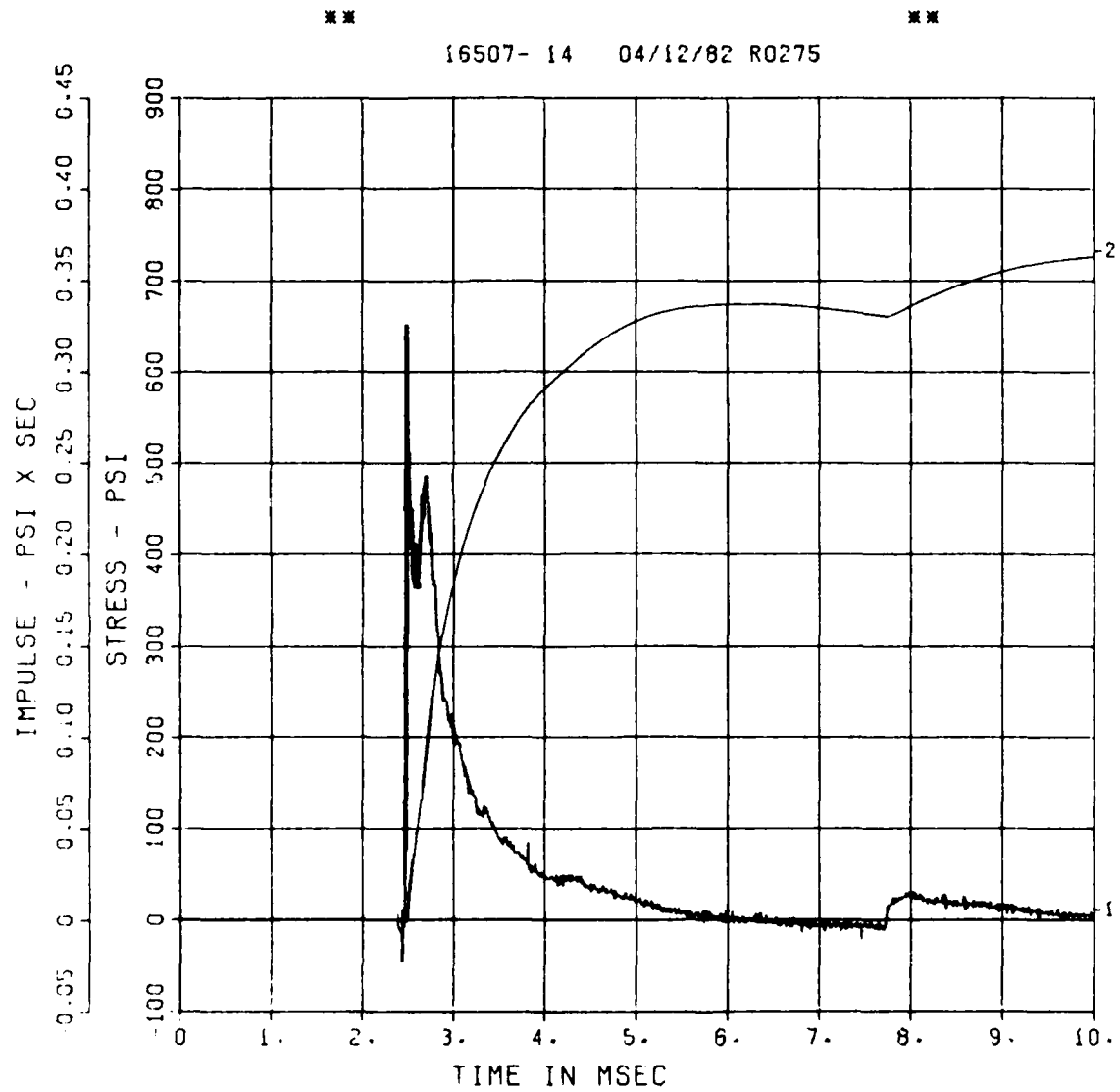


■ PEAK VALUE IS 15 % OVER CALIBRATION ■

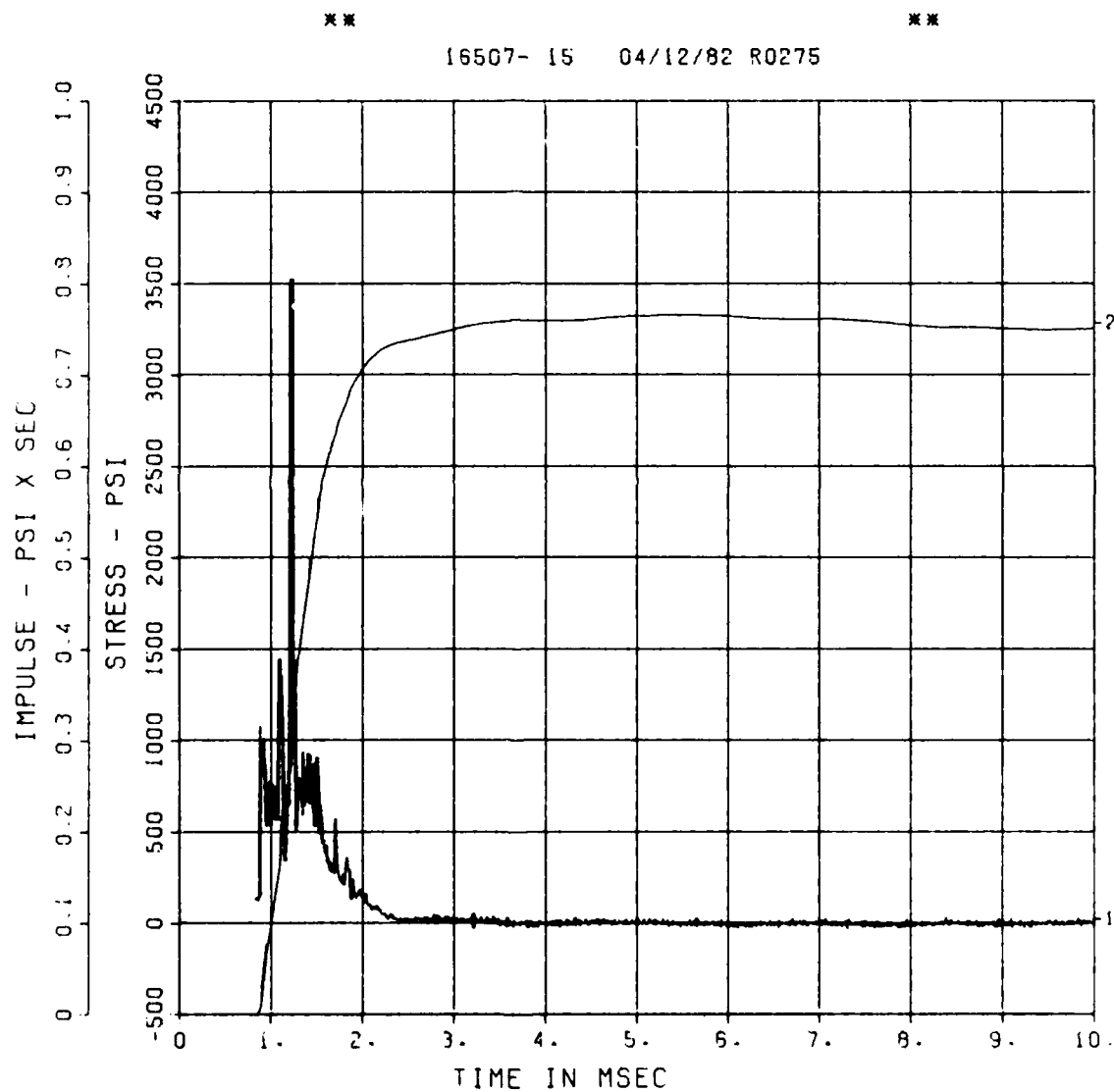
DHF BARE C4
PM2
200000. HZ CAL= 2214.



DHF BARE C4
PM3
200000. HZ CAL= 682.2



DHF BARE C4
PQ1
200000. HZ CAL= 2815.



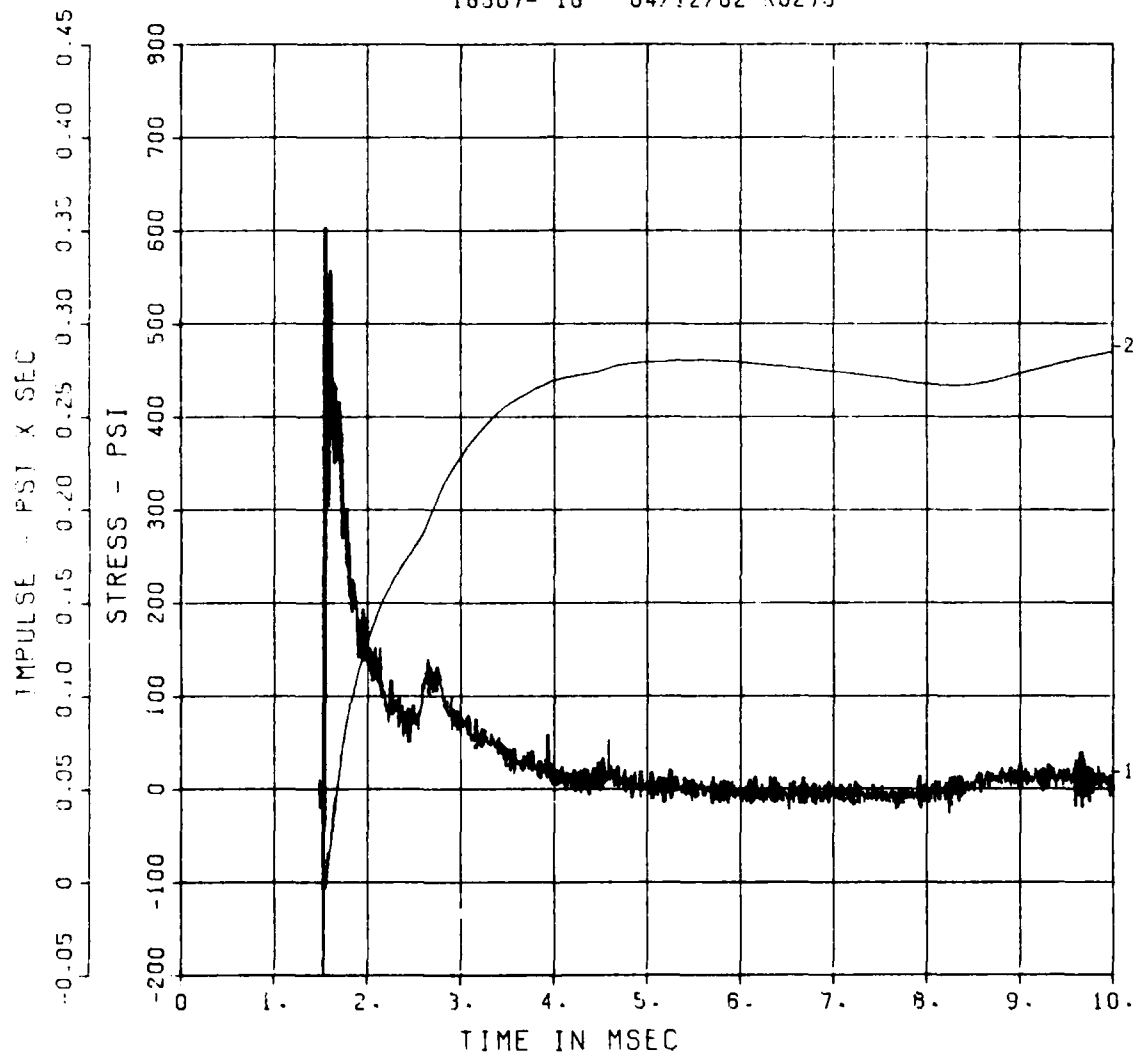
■ ■ PEAK VALUE IS 25 % OVER CALIBRATION ■ ■

DHF BARE C4
PQ2
200000. HZ CAL= 1942.

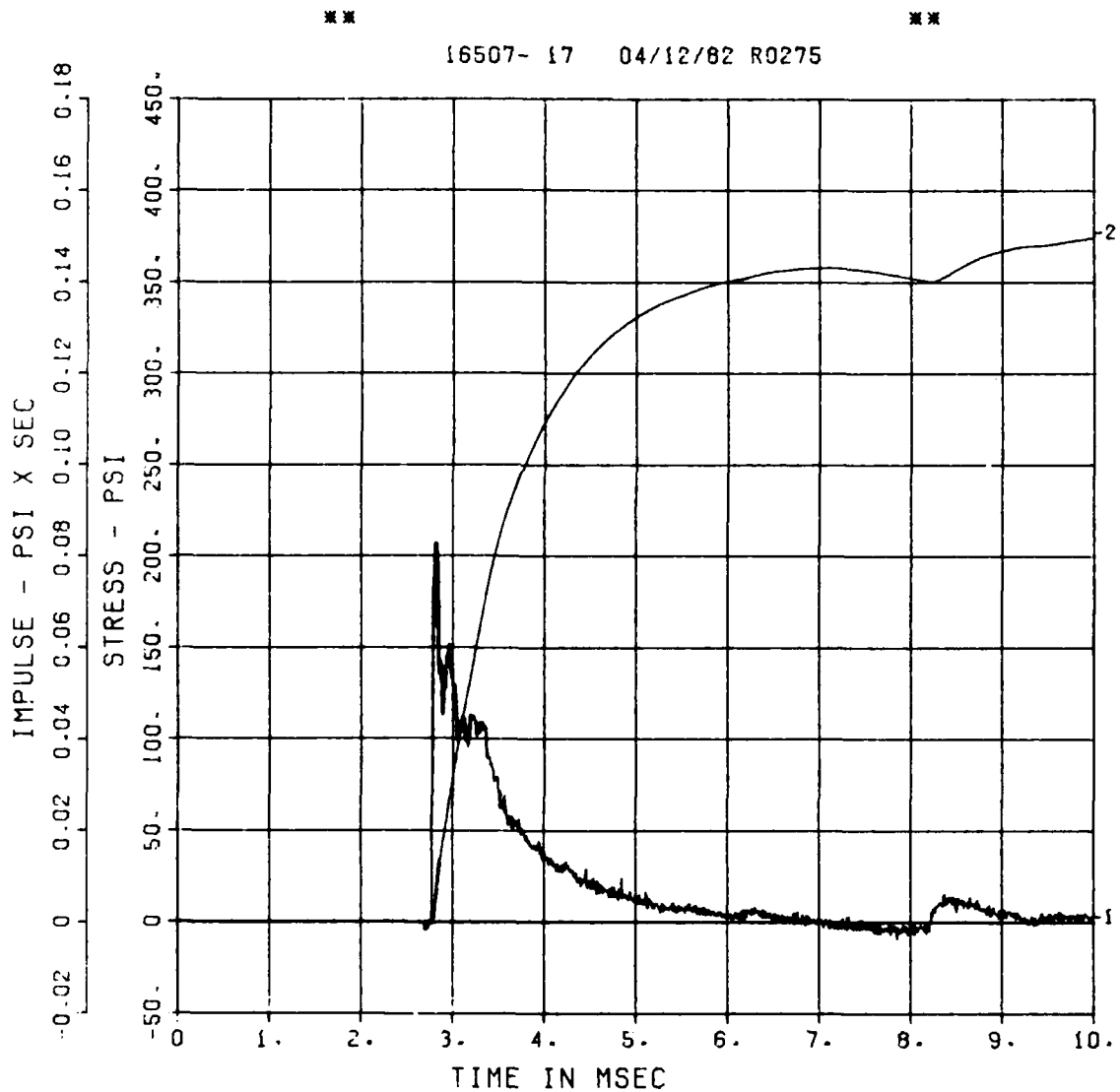
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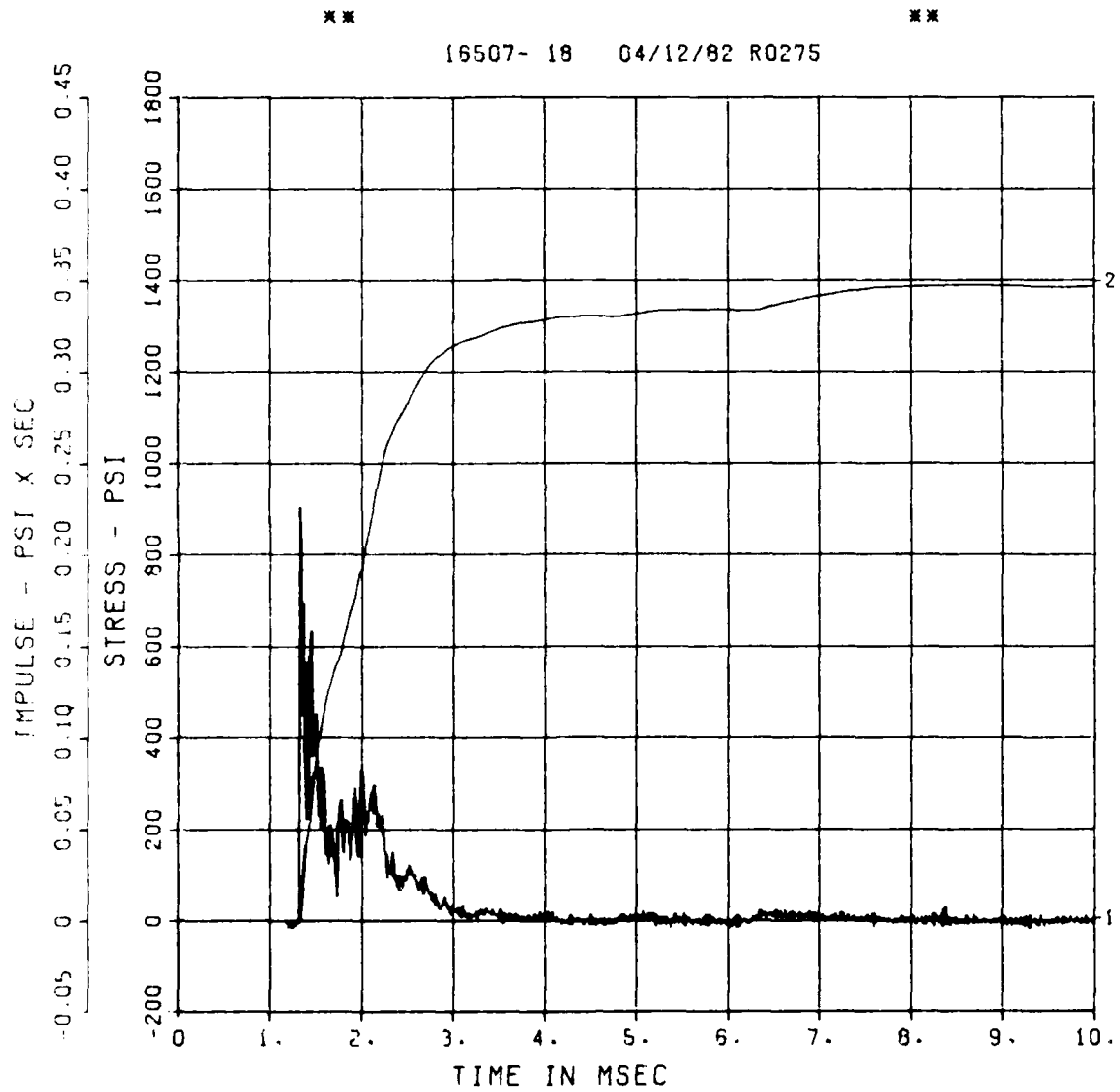
16507- 16 04/12/82 R0275



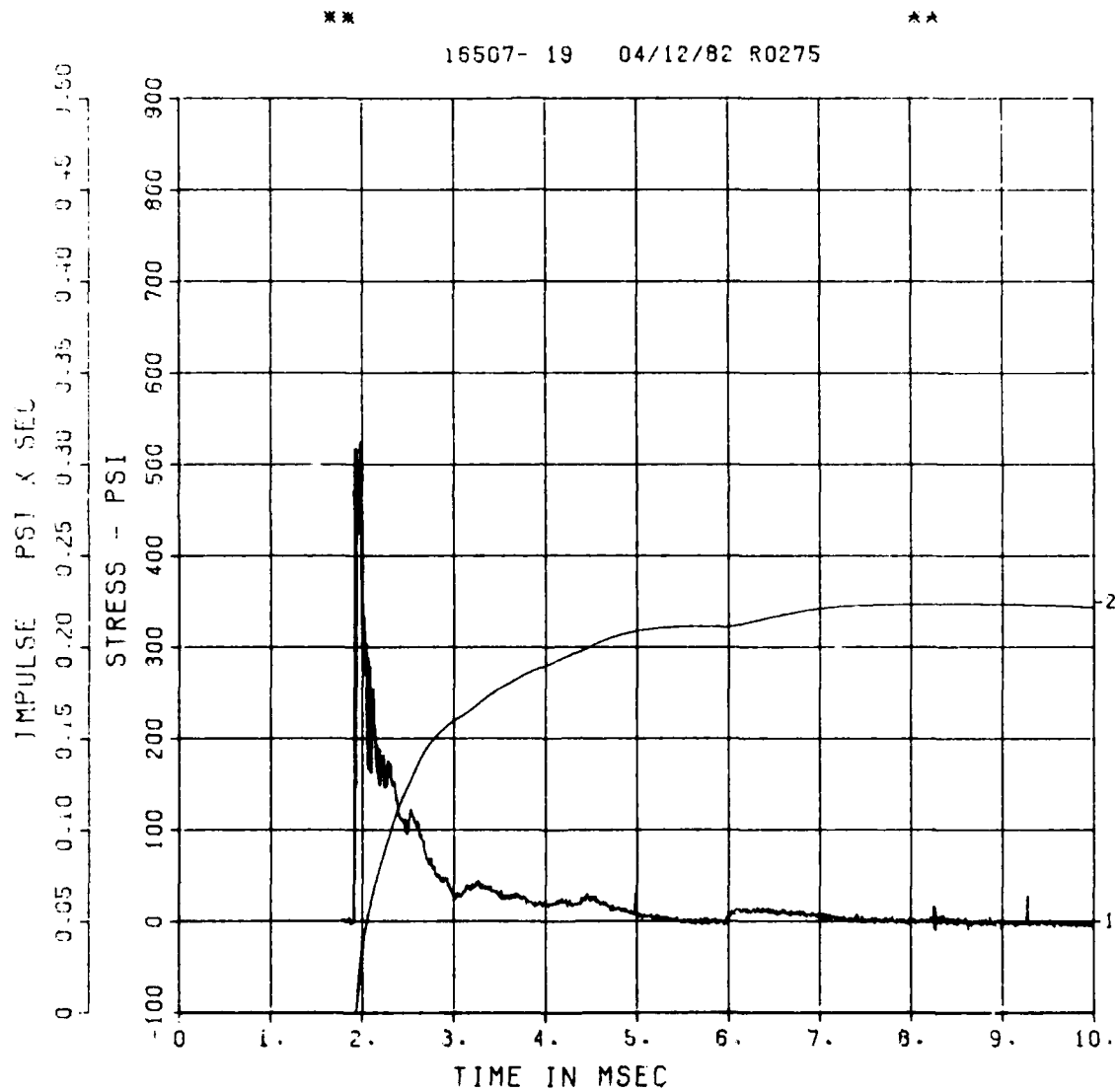
DHF BARE C4
PQ3
200000. HZ CAL= 677.0



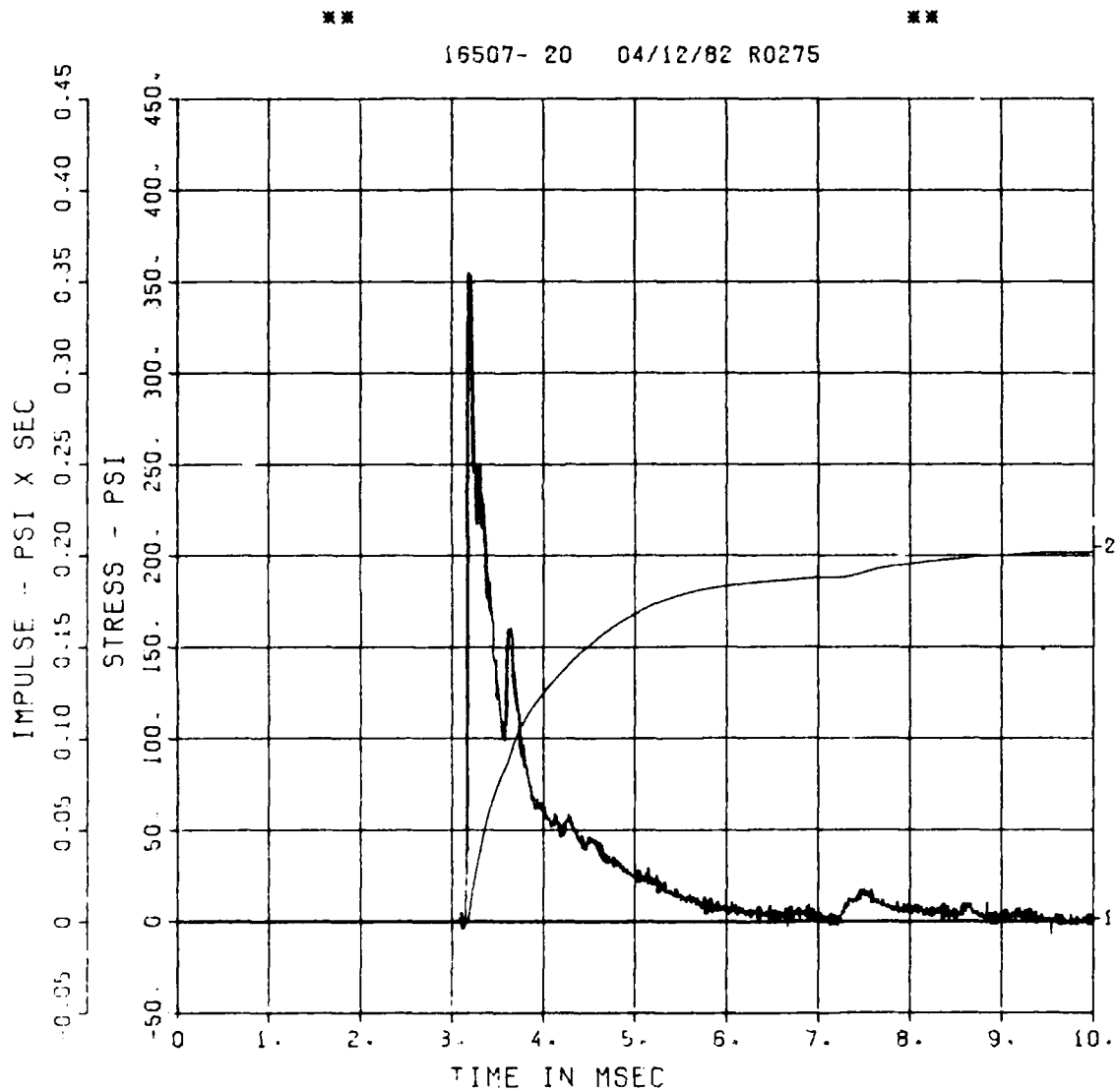
DHF BARE C4
PS1
200000. HZ CAL= 1696.



DHF BARE C4
PS2
200000. HZ CAL= 756.0



DHF BARE C4
PS3
200000. HZ CAL= 536.0



APPENDIX B
COMPARISON OF TIME-OF-ARRIVAL DATA



DEPARTMENT OF THE AIR FORCE

AIR FORCE WEAPONS LABORATORY (AFSC)
KIRTLAND AIR FORCE BASE, NM 87117

REPLY TO
ATTN OF

NTEDS

9 Jun 1982

SUBJECT

DHF TESTS, April 82

TO Waterways Experimental Station

1. QUESTION:

Relative energy from: Bare TNT
Bare C-4
Cased TNT

2. DISCUSSION:

Data from pressure gages was plotted. Results are inconclusive.

TOA vs. slant range was plotted for each line of gages on the wall (PM, PQ, PS). It was considered that the shock from the more energetic source would arrive earlier. In all cases, the shock from the bare C-4 arrives earlier than from the bare TNT. The difference between cased and uncased TNT is not clear except for the PS line.

It was considered that the data from the PS line would be more readable and that the farthest point would be the most accurate. However, to check this assumption the relative energy was calculated for all points using the SEDOV similarity solution for the spherical case.

SEDOV SIMILARITY SOLUTION (SPHERICAL CASE)

APPLIED TO SHOCK ARRIVAL DATA FROM DHF TESTS

Point	Slant Range (ft)	Relative Energy (C-4) (TNT)	Average
PM2	10.88	1.31	1.21
PM3	15.83	1.12	
PQ1	9.97	1.44	1.42
PQ2	12.43	1.57	
PQ3	16.92	1.26	
PS1	14.4	1.56	1.46
PS2	16.2	1.48	
PS3	19.86	1.34	
AVE.		1.38	

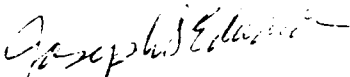
3. COMPARISON OF POINTS:

Scatter in the calculated energies was not unusually large ($\pm 15\%$). Average comparative energy from all points indicates that C-4 is 38 percent more energetic than TNT. The farthest point (PS3) indicates that C-4 is 34 percent more energetic than TNT.

4. CONCLUSION:

C-4 is more energetic than TNT. A value of 34 to 38 percent appears credible.

On the average, the airblast from uncased TNT appears to be higher than from cased TNT.



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